# Solar Advisor Model

## DRAFT CSP Reference Manual

Friday, December 05, 2008

SAM Version 2.5

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# 1 Overview

This draft reference manual describes the methodology used by the Solar Advisor Model's performance model for CSP parabolic trough systems. It applies to version 2.5 of the software. This manual does not explain cost or financial calculations. For information on costs, financial, and incentive calculations, see Solar Advisor's help system or user guide, the Solar Advisor website, and discussion group.

This draft has not been fully reviewed and may contain errors.

If you have questions about the Solar Advisor Model or comments about this manual, please contact us at Solar_Advisor_Support@nrel.gov.

# 2 Variable Naming Conventions

Variable names are assigned a letter indicating the type of variable with a subscript describing the variable. For example, the temperature correction factor used in the power block calculations uses the symbol $F_{\mathrm{TempCorr}}$.

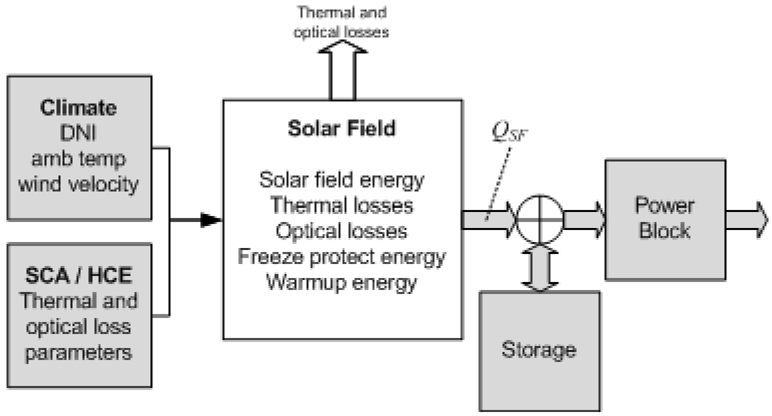
| Variable Symbol | Description | Units |
|---|---|---|
| $P$ | power rating | We or Wt |
| $E$ | electric generation | We |
| $Q$ | thermal energy | Wh |
| $Q''$ | thermal flux | W/m$^2$ |
| $F$ | multiplier factor | none |
| $N$ | quantity or number | none |
| $t$ | time | hours |
| $D$ | length | m |
| $v$ | velocity | m/s |

# 3 Solar Field

The Solar Field module calculates the net thermal energy delivered by the solar field $Q_{\mathrm{SF}}$ and other related energy quantities in each hour of the simulation. The delivered thermal energy calculations depend on the solar field size, solar position and collector orientation, the size and number of solar collector assemblies (SCAs), heat transfer fluid (HTF) type, and losses. The calculations account for the following losses:

- Heat collection element (HCE) end losses
- HCE heat loss
- Shadowing losses
- Piping heat losses
- Energy required for freeze protection
- Warm-up energy

**Fig 3.1. Diagram of the solar field module**




## 3.1 User Input Variables

### Layout

The layout variables on the Solar Field page determine the dimensions of the solar field. SAM provides two options for defining the solar field size: the Solar Multiple mode and Solar Field Area mode. In Solar Multiple mode, SAM calculates a solar field area that will, under reference conditions and accounting for heat losses, generate sufficient energy to drive the power block turbine at the "Design Turbine Gross Output" level. In Solar Field Area mode, SAM uses the user-defined solar field area, and calculates the equivalent Solar Multiple.

The tables below list each input variable on the Solar Field page, and briefly describes each variable and where it is used in calculations. The calculations are described in more detail in the sections following these tables.

**Table 3.1. Solar field layout variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Solar Multiple | When the radio button is active, the Layout mode is Solar Multiple, and the solar field area is calculated based on the value of the user-defined solar multiple. Note that SAM uses the solar multiple and solar field area shown under Calculated Values for calculations. | -- | -- |
| Solar Field Area | When the radio button is active, the Layout mode is Solar Field Area, and the solar multiple is calculated based on the user-defined solar field area. Note that SAM uses the solar multiple and solar field area shown under Calculated Values for calculations. | $m^2$ | -- |
| Distance Between SCAs in Row | The distance in meters between SCAs (solar collection elements, or collectors) in each row, assuming that SCAs are laid out uniformly throughout the solar field. SAM uses this value to calculate the end loss. | m | $D_{\mathrm{SCA}}$ |
| Distance Between Rows of SCAs | The distance in meters between rows of SCAs, assuming that rows are laid out uniformly throughout the solar field. SAM uses this value to calculate losses due to SCA-to-SCA shadowing. | m | $D_{\mathrm{SCARow}}$ |
| Number of SCAs per Row | The number of SCAs in each row, assuming that each row in the solar field has the same number of SCAs. SAM uses this value in the SCA end loss calculation. | -- | $N_{\mathrm{SCAPerRow}}$ |
| Deploy Angle | The SCA angle during the hour of deployment. A deploy angle of zero for a northern latitude is vertical facing due east. SAM uses this value to calculate the hour of deployment, which is the hour before the first hour of operation in the morning. SAM assumes that this angle applies to all SCAs in the solar field. | º | $\theta_{\mathrm{Deploy}}$ |
| Stow Angle | The SCA angle during the hour of stow. A stow angle of zero for a northern latitude is vertical facing east, and 180 degrees is vertical | º | $\theta_{\mathrm{Stow}}$ |

| Name | Description | Units | Symbol |
|---|---|---|---|
| | facing west. SAM uses this value to calculate the hour of stow, which is the hour after the final hour of operation in the evening. | | |

## Solar Multiple (Design Point)

The design point variables describe the reference weather conditions, equipment design parameters, and thermal losses under reference conditions that are used to calculate the solar field area when the layout mode is Solar Multiple. SAM also uses some of these variables to normalize certain values to design conditions. Note that some parameters and quantities used in calculations are represented by both a design value and an actual value. Actual values are calculated during simulation and vary with weather and equipment conditions. Design values (indicated in variable symbols by the word "Design" or letter "D") are used for sizing calculations and initial estimates.

**Table 3.2. Solar Multiple (Design Point) input variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Solar Multiple (calculated) | The solar field area expressed as a multiple of the exact area. SAM uses this value to calculate the design solar field thermal energy. | -- | $F_{\mathrm{SolarMultiple}}$ |
| Solar Field Area (calculated) | The solar field area expressed in square meters. SAM uses this value to calculate the solar field temperature, thermal energy delivered, thermal losses, and other related values. This value is used only if the Solar Field Area radio button is active. When it is not active, SAM uses the Solar Field Area (calculated value). | $m^2$ | $A_{\mathrm{SolarField}}$ |
| Ambient Temperature | Reference ambient temperature in degrees Celsius. Used to calculate the design solar field piping heat losses. | ºC | $T_{\mathrm{AmbientRef}}$ |
| Direct Normal Radiation | Reference direct normal radiation in Watts per square meter. Used to calculate the solar field area that would be required at this insolation level to produce the turbine's design thermal input. | $W/m^2$ | $Q''_{\mathrm{DNIRef}}$ |
| Wind Velocity | Reference wind velocity in meters per second. Used to calculate the design HCE heat losses. | m/s | $v_{\mathrm{WindRef}}$ |
| Exact Area | The solar field area required to deliver sufficient solar energy to the power block to drive the steam turbine at its design turbine gross output capacity under reference weather conditions. It is equivalent to a solar multiple of one, and used to calculate the solar field area when the Layout mode is Solar Multiple. | $m^2$ | $A_{\mathrm{SolarFieldExact}}$ |
| Exact Number of SCAs | Number of SCAs calculated based on solar field exact area and SCA aperture area. | | |
| Aperture Area per SCA | SCA aperture area variable from SCA / HCE page. | $m^2$ | $A_{\mathrm{SCAAperture}}$ |
| HCE Thermal Losses | Design HCE thermal losses calculated using heat loss parameters on SCA / HCE page. This value is used only for solar field sizing calculations and is different from hourly HCE thermal losses calculated during simulation and described in the SCA / HCE chapter. | $W/m^2$ | $Q''_{\mathrm{HCELossD}}$ |
| Optical Efficiency | Weighted optical efficiency variable from SCA / HCE page. Used only for solar field sizing calculations and is different from the value calculated during simulations, which is described in the SCA / HCE chapter. | -- | $F_{\mathrm{SFOpticalEffD}}$ |
| Design Turbine Thermal Input | Design turbine thermal input variable from Power Block page. Used to calculate exact area. | MWt | $Q_{\mathrm{PBDesign}}$ |

| Name | Description | Units | Symbol |
|---|---|---|---|
| Solar Field Piping Heat Losses | Design solar field piping heat losses. This value is used only for solar field sizing calculations, and is different from the hourly pipe heat losses calculated during simulation and described later in this chapter. | W/m$^2$ | $Q''_{\mathrm{SFPipeLossD}}$ |

## Heat Transfer Fluid

The heat transfer fluid (HTF) parameters describe solar field properties that affect the HTF temperature calculations during the hourly simulation. Note that the value of the minimum HTF temperature is stored in the HTF type library, and by default is different for heat HTF type.

**Table 3.3. Heat Transfer Fluid input variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Solar Field HTF | Name of the heat transfer fluid type. The Minimum HTF Temperature value depends on the HTF type. | -- | -- |
| Solar Field Inlet Temperature | Design temperature of the solar field inlet in degrees Celsius used to calculate design solar field average temperature, and design HTF enthalpy at the solar field inlet. SAM also limits the solar field inlet temperature to this value during operation and solar field warm up, and uses this value to calculate the actual inlet temperature when the solar field energy is insufficient for warm-up. | ºC | $T_{\mathrm{SFinD}}$ |
| Solar Field Outlet Temperature | Design temperature of the solar field outlet in degrees Celsius, used to calculate design solar field average temperature. It is also used to calculate the design HTF enthalpy at the solar field outlet, which SAM uses to determine whether solar field is operating or warming up. SAM also uses this value to calculate the actual inlet temperature when the solar field energy is insufficient for warm-up. | ºC | $T_{\mathrm{SFoutD}}$ |
| Solar Field Initial Temperature | Initial solar field inlet temperature. The solar field inlet temperature is set to this value for hour one of the simulation. | ºC | $T_{\mathrm{SFinInit}}$ |
| Solar Field Piping Losses @ Design T | Solar field piping heat loss in Watts per square meter of solar field calculated based on design variables. Used in solar field heat loss calculation. | W/m$^2$ | $Q_{\mathrm{PHLD}}$ |
| Piping Heat Loss coefficients (3) | These three values are used with the solar field piping heat loss at design temperature to calculate solar field piping heat loss. | -ºC$^{-1}$, -ºC$^{-2}$, -ºC$^{-3}$ | $F_{\mathrm{PHL}}$ |
| Minimum HTF Temperature | Minimum heat transfer fluid temperature in degrees Celsius. Determines when freeze protection energy is required, and is used to calculate HTF enthalpies for the freeze protection energy calculation, and is the lower limit of the average solar field temperature. | ºC | $T_{\mathrm{HTFMin}}$ |
| HTF Gallons Per Area | Volume of HTF per square meter of solar field, used to calculate the total mass of HTF in the solar field, which is used to calculate solar field temperatures and energies during hourly simulations. | gal/m$^2$ | $V_{\mathrm{HTF}}$ |
| HTF Flow Control | NOTE FOR REVIEW: IN EXCELERGY, CONSTANT FLOW APPEARS TO BE ONLY FOR ORC. I DONT SEE IT IN TRNSYS CODE. | | |
| Night Time Flow Control | NOTE FOR REVIEW: IN EXCELERGY, VALUE IS READ IN BUT DOES NOT APPEAR TO BE USED. DOES NOT APPEAR TO BE USED IN TRNSYS CODE. | | |

**Table 3.4. Orientation and Tracking**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Collector Tilt | For single-axis tracking systems, collector angle from horizontal, where zero degrees is horizontal. Used to calculate incident solar radiation. | º | $\theta_{\mathrm{ColTilt}}$ |
| Collector Azimuth | For single-axis tracking systems. azimuth angle of collector, where zero degrees is due south, equivalent to a north-south axis. Used to calculate incident solar radiation. | radians | $\theta_{\mathrm{ColAz}}$ |
| Single axis tracking | Collector rotates about line defined by collector azimuth to follow daily motion of the sun across the sky. | | |
| Two-axis tracking | NOTE FOR REVIEW: DOES NOT MAKE SENSE FOR TROUGH | | |

## 3.2 Weather Data

SAM reads data from weather files in two formats: typical meteorological year 2 ("tm2" file extension) and EnergyPlus ("epw" file extension). The location on the Climate page determines which weather file is used for the simulation. Weather files must be stored in /Data/WeatherFiles folder to appear in the location list on the Climate page.

**Table 3.5. Data elements from weather files used by SAM**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Local standard time | Day of year, month, hour of month, day of month, and hour of day. Used to calculate hour of year. | | |
| Direct normal radiation | Amount of solar radiation received in one hour within a limited field of view centered on the sun. | W/m² | $Q_{NIP}$ |
| Wind velocity | Average velocity of the wind for the hour. | m/s | $v_{Wind}$ |
| Solar azimuth angle | Average solar azimuth angle for the hour. The angle between the line from the collector to the sun projected on the ground, and the line from the collector due south. | ° | $\theta_{\mathrm{SolAz}}$ |
| Ambient temperature | Average dry bulb temperature for the hour. | °C | $T_{Ambient}$ |
| Wet bulb temperature | This value is not included in the weather file data, but is calculated by SAM based on the dry bulb temperature, dew point temperature and relative humidity data from the weather file.This value is used by the Power Block module for temperature correction calculations. | °C | $T_{\mathrm{WetBulb}}$ |
| Latitude | Degrees north or south of the equator of the project site. | ° | $\theta_{Latitude}$ |
| Longitude | Site longitude. | ° | $\theta_{Longitude}$ |

## 3.3 Solar Field Size

The Layout mode on the Solar Field page determines how SAM calculates the solar field size. Note that the solar multiple and solar field area values used for simulation calculations are shown on the Solar Field page with blue backgrounds under Calculated Values.

When the Layout mode is Solar Multiple, SAM calculates the solar field area $A_{\mathrm{SolarField}}$ based on the value of the user-defined solar multiple:

$$A_{\mathrm{SolarField}} = A_{\mathrm{SolarFieldExact}} \cdot F_{\mathrm{SolarMultiple}} \tag{3.1}$$

Similarly, when the Layout mode is Solar Field Area, SAM calculates the solar multiple $F_{\mathrm{SolarMultiple}}$ based on the user-defined solar field area:

$$F_{\text{SolarMultiple}} = \frac{A_{\text{SolarField}}}{A_{\text{SolarFieldExact}}} \quad (3.2)$$

The exact area $A_{\text{SolarFieldExact}}$, equivalent to a solar multiple of one, is the solar field area required to generate sufficient thermal energy under the design point reference conditions to supply the design turbine thermal input defined on the Power Block page.

$$A_{\text{SolarFieldExact}} = \frac{Q_{\text{PBDesign}}}{Q_{\text{DNIRef}} \cdot F_{\text{SFOpticalEffD}} - Q_{\text{HCELossD}} - Q_{\text{SFPipeLossD}}} \quad (3.3)$$

The design values of the HCE thermal loss $Q_{\text{HCELossD}}$ that appears on the SCA / HCE page and the solar field piping thermal loss $Q_{\text{SFPipeLossD}}$ that appears on the Solar Field page are different from the hourly loss values calculated during simulation. The design values are used in the solar field area calculations shown above, which are completed before the simulation. A similar set of equations discussed later in this chapter are used during simulation, but use hourly temperature values from the weather data file instead of the reference values. The design solar field piping thermal loss is calculated as follows:

$$Q_{\text{SFPipeLossD}} = \left(F_{\text{PHL3}} \cdot \Delta T_{\text{SFD}}^{\;3} + F_{\text{PHL2}} \cdot \Delta T_{\text{SFD}}^{\;2} + F_{\text{PHL1}} \cdot \Delta T_{\text{SFD}}\right) \cdot Q_{\text{PHLatDsgnT}} \quad (3.4)$$

$$\Delta T_{\text{SFD}} = \frac{T_{\text{SFinD}} + T_{\text{SFoutD}}}{2} - T_{\text{AmbientRef}} \quad (3.5)$$

## 3.4 Design Variables

The design variables store solar field performance parameters under design conditions. They are used in simulation calculations to normalize temperature and energy values to the design values. The design variables are:

- Design solar field inlet and outlet temperatures, $T_{\text{SFinD}}$ and $T_{\text{SFoutD}}$
- HTF design enthalpies at the solar field inlet and outlet, $H_{\text{inDesign}}$ and $H_{\text{outDesign}}$
- Design solar field energy, $Q_{\text{SFDesign}}$
- Design solar field mass flow, $m_{\text{SFMassFlowD}}$
- HTF gallons per area, $V_{\text{HTF}}$

### User input design variables

The user-defined design variables are:

- Solar field inlet temperature, $T_{\text{SFinD}}$
- Solar field outlet temperature, $T_{\text{SFoutD}}$
- HTF gallons per area, $V_{\text{HTF}}$

Note that the minimum HTF temperature value $T_{\text{HTFMin}}$ is automatically populated based on the solar field HTF type. Changing the HTF type changes the minimum HTF temperature.

### Calculated design variables

The HTF design enthalpy at the solar field inlet and outlet depends on the type of HTF and are a function of the design solar field inlet and outlet temperatures, $T_{\text{SFinD}}$ and $T_{\text{SFoutD}}$, respectively.

The solar field design thermal energy $Q_{\mathrm{SFDesign}}$ is the energy that the solar field must deliver under the design point reference conditions to supply the power block's design turbine thermal input, which is the design turbine gross output $Q_{\mathrm{PBDesign}}$ divided by the design turbine gross efficiency $\eta_{\mathrm{PBDesign}}$:

$$Q_{\mathrm{SFDesign}} = \frac{Q_{\mathrm{PBDesign}}}{\eta_{\mathrm{PBDesign}}} \cdot F_{\mathrm{SolarMultiple}} \tag{3.6}$$

The design solar field mass flow, $m_{\mathrm{SFMassFlowD}}$ is used to calculate solar field outlet temperature.

$$m_{\mathrm{SFMassFlowD}} = \frac{Q_{\mathrm{SFDesign}}}{H_{\mathrm{outD}} - H_{\mathrm{inD}}} \tag{3.7}$$

## 3.5 HTF Properties

The heat transfer fluid (HTF) properties and mass equations are used for several solar field energy calculations described in Delivered Energy and Losses. SAM includes property lookup tables for the  seven HTF types:

- Nitrate salt
- Caloria HT 43
- Hitec XL
- Therminol VP-1
- Hitec
- Dowtherm Q
- Dowtherm RP

### Mass

The HTF mass is used to calculate the following values:

- Warm-up energy $Q_{\mathrm{Warmup}}$
- Freeze-protection energy $Q_{\mathrm{FreezeProtect}}$
- Average solar field temperature when solar field energy is below the design point $T_{\mathrm{SFAve}}$

The HTF mass $M_{\mathrm{HTF}}$ is calculated using the user-defined HTF volume per area $V_{\mathrm{HTF}}$. The conversion from gallons to liters is omitted for clarity:

$$V_{\mathrm{HTF}} = V_{\mathrm{HTFperArea}} \cdot A_{\mathrm{SolarField}} \tag{3.8}$$

$$M_{\mathrm{HTF}} = V_{\mathrm{HTF}} \cdot \rho_{\mathrm{HTF}} \tag{3.9}$$

The HTF density $\rho_{\mathrm{HTF}}$ is a function of the HTF temperature as show in the table below

**Table 3.6. HTF density as a function of temperature in degrees Celsius**

| HTF | Specific Heat Equation |
|---|---|
| Nitrate salt | $\rho = -6.36\times10^{-1} \cdot T + 2.090\times10^{3}$ |
| Caloria HT 43 | $\rho = -1.265\times10^{-4} \cdot T^2 - 6.617\times10^{-1} \cdot T + 8.85\times10^{2}$ |
| Hitec XL | $\rho = -8.266\times10^{-1} \cdot T + 2.240\times10^{3}$ |
| Therminol VP-1 | $\rho = -7.762\times10^{-4} \cdot T^2 - 6.367\times10^{-1} \cdot T + 1.0740\times10^{3}$ |

| HTF | Specific Heat Equation |
|---|---|
| Hitec | $\rho = -7.33\times10^{-1} \cdot T + 2.080\times10^{3}$ |
| Dowtherm Q | $\rho = -7.57332\times10^{-1} \cdot T + 9.80787\times10^{2}$ |
| Dowtherm RP | $\rho = -1.86495\times10^{-4} \cdot T^{2} - 6.68337\times10^{-1} \cdot T + 1.04211\times10^{3}$ |

## Enthalpy and temperature

HTF enthalpy is used to determine the thermal energy of the HTF as a function of temperature and vice versa. The equations are used to calculate:

- Average solar field temperature $T_{\mathrm{SFAve}}$ when the solar field energy is below the design point
- Freeze protection energy $Q_{\mathrm{FreezeProtect}}$
- Warm-up energy $Q_{\mathrm{Warmup}}$
- Design solar field mass flow rate $m_{\mathrm{SFMassFlowD}}$

**Table 3.7. HTF enthalpy in Joules per kilogram as a function of temperature in degrees Celsius**

| HTF | Enthalpy Equation |
|---|---|
| Nitrate salt | $H = 8.6\times10^{-2} \cdot T^{2} + 1.443\times10^{3} \cdot T$ |
| Caloria HT 43 | $H = 1.94 \cdot T^{2} + 1.6060\times10^{3} \cdot T$ |
| Hitec XL | $H = - 3.79667\times10^{-5} \cdot T^{3} - 1.312\times10^{-1} \cdot T^{2} + 1.536\times10^{3} \cdot T$ |
| Therminol VP-1 | $H = 1.377 \cdot T^{2}+ 1.498\times10^{3}\cdot T -1.8340\times10^{4}$ |
| Hitec | $H = 1.560\times10^{3} \cdot T$ |
| Dowtherm Q | $H = 1.51461 \cdot T^{2} + 1.59867\times10^{3} \cdot T - 2.50596\times10^{0}$ |
| Dowtherm RP | $H = 1.4879 \cdot T^{2} + 1.5609\times10^{3} \cdot T - 2.4798$ |

**Table 3.8. HTF temperature in degrees Celsius as a function of enthalpy in Joules per kilogram**

| HTF | Temperature Equation |
|---|---|
| Nitrate salt | $T = -2.62\times10^{-11} \cdot H^{2} + 6.923\times10^{-4} \cdot H + 3.058\times10^{-2}$ |
| Caloria HT 43 | $T = 6.4394\times10^{-17} \cdot H^{3} - 2.3383\times10^{-10}\cdot H^{2} + 5.821\times10^{-4}\cdot H + 1.2744$ |
| Hitec XL | $T = 5.111\times10^{-11} \cdot H^{2} + 6.466\times10^{-4} \cdot H + 2.151\times10^{-1}$ |
| Therminol VP-1 | $T = 7.4333\times10^{-17} \cdot H^{3} - 2.4625\times10^{-10} \cdot H^{2} + 6.3282\times10^{-4} \cdot H + 1.2403\times10^{1}$ |
| Hitec | $T = -3.309\times10^{-24} \cdot H^{2} + 6.41\times10^{-4} \cdot H + 1.364\times10^{-12}$ |
| Dowtherm Q | $T = 6.186\times10^{-17} \cdot H^{3} - 2.2211\times10^{-10} \cdot H^{2} + 5.9998\times10^{-4} \cdot H + 7.7742\times10^{-1}$ |
| Dowtherm RP | $T = 6.6607\times10^{-17} \cdot H^{3} - 2.3347\times10^{-10} \cdot H^{2} + 6.1419\times10^{-4} \cdot H + 7.7419\times10^{-1}$ |

## Specific heat

The specific heat equations are used to calculate the difference in temperature between the solar field inlet and outlet when the solar field output is zero.

**Table 3.9. HTF specific heat as a function of temperature in Joules per kilogram - degree Celsius**

| HTF | Heat Capacity Equation |
|---|---|
| Nitrate salt | $Cp = 1.72\times10^{-1} \cdot T + 1.443\times10^{3}$ |
| Caloria HT 43 | $Cp = 3.88 \cdot T + 1.606\times10^{3}$ |
| Hitec XL | $Cp = -1.139\times10^{-4} \cdot T^{2} - 2.624\times10^{-1} \cdot T + 1.536\times10^{3}$ |
| Therminol VP-1 | $Cp = 7.888\times10^{-4} \cdot T^{2} + 2.496 \cdot T + 1.509\times10^{3}$ |

| HTF | Heat Capacity Equation |
|---|---|
| Hitec | $Cp = 1.560\times10^3 - T$ |
| Dowtherm Q | $Cp = -5.3943\times10^{-4} \cdot T^2 + 3.2028 \cdot T + 1.5892\times10^3$ |
| Dowtherm RP | $Cp = -3.1915\times10^{-6} \cdot T^2 + 2.977 \cdot T + 1.5608\times10^3$ |

## 3.6 Collector and Sun Angles

The collector incident angles represent the relative positions of the collector and sun. The solar incidence angle, $\theta_{\text{SolarIncidence}}$, and incident angle modifier $F_{\text{IAM}}$ are used to calculate the thermal energy absorbed by the collector $Q_{\text{abs}}$ and the optical and thermal efficiency losses.

The solar incidence angle  depends on the sun's position and the orientation of the trough collectors. SAM assumes that all SCAs in the solar field have the same orientation. The time and sun's position are calculated based on the project location's latitude, longitude, and time zone from the weather file.

$$\theta_{\text{SolarIncidence}} = \text{acos}(F_{\text{SolarIncidence}}) \tag{3.10}$$

$$F_{\text{SolarIncidence}} = |1 - \cos(\theta_{\text{SolAlt}} - \theta_{\text{ColTilt}}) - \cos\theta_{\text{ColTilt}} \cdot \cos\theta_{\text{SolAlt}} \cdot [1 - \cos(\theta_{\text{SolAz}} - \theta_{\text{ColAz}})| \tag{3.11}$$

The incident angle modifier factor $F_{\text{IAM}}$ is an efficiency factor that accounts for collector efficiency losses due to of the collector aperture foreshortening,  glass envelope transmissivity, selective surface absorption and other losses. End losses are calculated separately. The incident angle modifier factor is calculated using an empirically derived formula based on field tests of the SEGS 2 project described in Dudley (1994). The three incidence angle modifier coefficients $F_{\text{IAM1}}$, $F_{\text{IAM2}}$, $F_{\text{IAM3}}$ are inputs on the SCA / HCE page.

$$F_{\text{IAM}} = F_{\text{IAM1}} + \frac{F_{\text{IAM2}}}{\cos(\theta_{\text{SolarIncidence}})} \cdot \theta_{\text{SolarIncidence}} + \frac{F_{\text{IAM3}}}{\cos(\theta_{\text{SolarIncidence}})} \cdot \theta_{\text{SolarIncidence}}{}^2 \tag{3.12}$$

For each hour of the simulation, SAM determines whether the solar field is in one of four operating modes:

- Operating: Current hour is between the deployment and stow hours
- Not operating: Current hour is between the stow and deployment hours
- Deploying: Solar field deploys in current hour
- Stowing: Solar field stows in current hour

The operating mode depends on the hour of the day, position of the sun, and the deploy and stow angle values on the Solar Field page.

The solar altitude $\theta_{\text{SolAlt}}$ and solar azimuth $\theta_{\text{SolAz}}$ values used in the equations above are calculated using standard algorithms as described in Duffie and Beckman and Stine. The algorithms require the following variables which are calculated from the time of day data in the weather file:

- current Julian day
- solar declination
- hour angle
- time shift from standard meridian

## 3.7 Delivered Energy and Losses

The energy delivered by the solar field $Q_{\text{SF}}$, depends on the following factors:

- Solar energy absorbed by the collectors

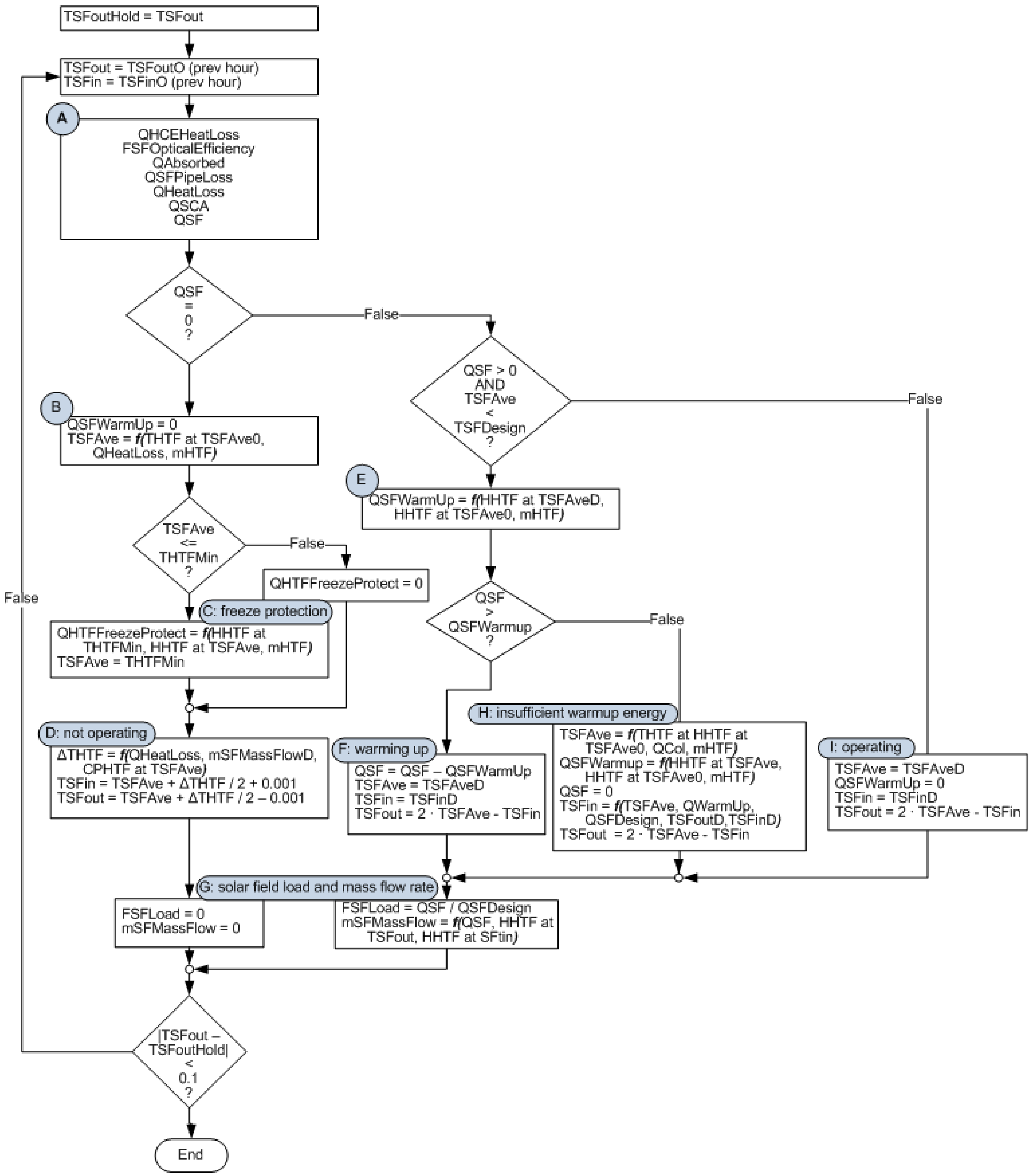
- Solar field temperatures, which depend on the HTF properties
- Solar field heat losses

SAM calculates three solar field temperatures, the inlet temperature $T_{\mathrm{SFin}}$, outlet temperature $T_{\mathrm{SFout}}$, and average temperature $T_{\mathrm{SFAve}}$ as shown in the figure below. The HCE heat loss calculation (see A in the diagram and its description below) requires the solar field outlet temperature, which is not calculated until later in the code (D, F, H, and I in the diagram). Because of this, the algorithm uses iteration to find the outlet temperature. The variable $T_{\mathrm{SFoutHold}}$ is used to store the solar field outlet temperature value from the previous iteration.

There are four operating conditions shown in the diagram requiring different equations to calculate the three solar field temperatures. The operating conditions depend on the value of the solar field energy $Q_{\mathrm{SF}}$ (calculated in A in the diagram).

- When the solar field energy $Q_{\mathrm{SF}}$ is zero, the solar field does not operate (D in the schematic). When the solar field is not operating, a freeze protection energy requirement is calculated that is sufficient to prevent the HTF temperature from dropping below its minimum allowed value (C). Only systems that include thermal energy storage and/or fossil backup will be able to supply this energy.
- When the solar field energy is greater than zero and the average solar field temperature is greater than the design temperature, the solar field operates (I).
- When the solar field energy is less than zero or the average solar field temperature is less than the design temperature, the required warm-up energy is calculated (E). If the solar field energy is greater than the warm-up energy, the solar field warms up (F), otherwise, the solar field does not warm up and loses energy (H).

**Figure 3.2. Diagram of the solar field energy calculations. Use the letters to find explanations and equations in the text below the schematic.**




## Initial solar field energy and heat loss equations (A)

This set of equations applies under all solar field operating conditions.

### Solar field optical efficiency

The solar field optical efficiency $F_{\text{SFOpticalEfficiency}}$ accounts for the SCA optical efficiency, row shadowing and end losses, and incident angle-related losses.

$$F_{\text{SFOpticalEfficiency}} = F_{\text{SCAOpticalEfficiency}} \cdot F_{\text{RowShadow}} \cdot F_{\text{EndLoss}} \cdot F_{\text{IAM}} \tag{3.13}$$

The SCA optical efficiency, and the row shadow and end loss factors are described in the SCA / HCE chapter.

### Absorbed energy

The thermal energy absorbed by the HCEs $Q_{\text{Absorbed}}$ in thermal Watts/m$^2$ depends on the solar incidence angle $\theta_{\text{SolarIncidence}}$, incident solar radiation from the weather file $Q_{\text{NIP}}$, solar field optical efficiency $F_{\text{SFOpticalEfficiency}}$ from the SCA / HCE module, and the solar field availability factor $F_{\text{Availability}}$ from the SCA / HCE input page.

$$Q_{\text{Absorbed}} = \cos(\theta_{\text{SolarIncidence}}) \cdot Q_{\text{NIP}} \cdot F_{\text{SFOpticalEfficiency}} \cdot F_{\text{Availability}} \tag{3.14}$$

### Solar field pipe heat loss

The solar field pipe heat loss $Q_{\text{SFPipeLoss}}$ in W/m$^2$ is a function of the three pipe heat loss temperature coefficients on the Solar Field page, the solar field temperature difference $\Delta T$, and the solar field piping heat loss at design T factor $F_{\text{PHLatDsgnT}}$ on the Solar Field page.

$$Q_{\text{SFPipeLoss}} = \left(F_{\text{PHL3}} \cdot \Delta T^3 + F_{\text{PHL2}} \cdot \Delta T^2 + F_{\text{PHL1}} \cdot \Delta T\right) \cdot F_{\text{PHLD}} \tag{3.15}$$

The solar field temperature difference $\Delta T$ in degrees Celsius is a function of the solar field average temperature $T_{\text{SFAve}}$, and the ambient temperature from the weather file $T_{\text{Ambient}}$:

$$\Delta T = T_{\text{SFAve}} - T_{\text{Ambient}} \tag{3.16}$$

The solar field average temperature $T_{\text{SFAve}}$ in degrees Celsius at is a function of the solar field inlet and outlet temperatures:

$$T_{\text{SFAve}} = \frac{T_{\text{SFin}} + T_{\text{SFout}}}{2} \tag{3.17}$$

### Total solar field heat loss

The total heat loss $Q_{\text{HeatLoss}}$ in thermal Watts is the sum of HCE thermal losses $Q_{\text{HCELoss}}$ and solar field pipe losses $Q_{\text{SFPipeLoss}}$. $Q_{\text{HCELoss}}$ is calculated in the SCA / HCE module.

$$Q_{\text{HeatLoss}} = Q_{\text{HCELoss}} + Q_{\text{SFPipeLoss}} \tag{3.18}$$

The HCE heat loss $Q_{\text{HCELoss}}$ equations are based on values on the SCA / HCE page and are described in the SCA / HCE chapter.

### SCA (collector) energy

The SCA energy $Q_{\mathrm{SCA}}$ in W/m$^2$ is the absorbed energy less solar field heat loss $Q_{\mathrm{HeatLoss}}$.

$$Q_{\mathrm{SCA}} = Q_{\mathrm{Absorbed}} - Q_{\mathrm{HeatLoss}} \tag{3.19}$$

### Initial solar field energy

The solar field delivered energy $Q_{\mathrm{SF}}$ in thermal Watts is the energy delivered by the solar field to the power block and storage modules. Note that this is an initial value that determines whether the solar field operates or not in the current hour. The value may be recalculated or modified as shown in the schematic diagram and described below.

$$Q_{\mathrm{SF}} = Q_{\mathrm{SCA}} \cdot A_{\mathrm{SolarField}} \tag{3.20}$$

## QSF is zero

When the solar field energy $Q_{\mathrm{SF}}$ is zero, SAM calculates the average solar field temperature based on the HTF temperature, determines whether freeze protection energy is required, and then calculates the solar field inlet and outlet temperatures.

Note that in the following equations, enthalpy variable name subscripts indicate the temperature at which the enthalpy is calculated. For example, the enthalpy variable $H_{\mathrm{HTFatTSFout}}$ is the HTF enthalpy at the solar field outlet temperature $T_{\mathrm{SFout}}$. The lookup tables in the HTF Properties section show the temperature-to-enthalpy equations for each HTF type. Similarly, the subscripts for temperature variables indicate the enthalpy value to use for enthalpy-to-temperature equations, which can also be found in the lookup tables.

### Average solar field temperature B

Because no solar energy is available to heat the HTF, the solar field temperature is determined by the HTF temperature:

$$T_{\mathrm{SFAve}} = T_{\mathrm{HTFatHHTF}} \tag{3.21}$$

The HTF temperature $T_{\mathrm{HTFatHHTF}}$ is calculated using the appropriate equation from the HTF enthalpy lookup table, where the HTF enthalpy is the enthalpy of the previous hour less the solar field heat losses in the current hour:

$$H_{\mathrm{HTF}} = H_{\mathrm{HTFatTSFAve0}} - \frac{Q_{\mathrm{HeatLoss}} \cdot A_{\mathrm{SolarField}}}{M_{\mathrm{HTF}}} \tag{3.22}$$

where $H_{\mathrm{HTFatTSFAve0}}$ is the HTF enthalpy at the solar field average temperature of the previous hour, and $M_{\mathrm{HTF}}$ is the mass of the HTF in kilograms. Under these conditions, the solar field warmup energy is zero.

$$Q_{\mathrm{SFWarmUp}} = 0 \tag{3.23}$$

### Freeze protection energy C

When the solar field energy is zero and the average solar field temperature $T_{\mathrm{SFAve}}$ is above the minimum HTF temperature $T_{\mathrm{HTFmin}}$, no energy for freeze protection is required. When the average solar field $T_{\mathrm{SFAve}}$ is below

$T_{\text{HTFMin}}$, the system requires energy for freeze protection. Note that this energy must be supplied by either a thermal energy storage system or a fossil backup system. The energy required for freeze protection for the current hour is a function of the HTF enthalpy at its freezing point $T_{\text{HTFMin}}$, the solar field average temperature during the hour, and the HTF mass in kilograms:

$$Q_{\text{HTFFreezeProtect}} = (H_{\text{HTFatTHTFMin}} - H_{\text{HTFatTSFAve}}) \cdot M_{\text{HTF}} \tag{3.24}$$

After the required freeze protection energy is calculated, the average solar field temperature is set to the HTF's freezing point, $T_{\text{HTFMin}}$:

$$T_{\text{SFAve}} = T_{\text{HTFMin}} \tag{3.25}$$

### Solar field inlet and outlet temperatures D

When the solar field output is zero, after calculating the average solar field temperature and required freeze protection energy, SAM calculates the difference in temperature between the solar field inlet and outlet ΔTHTF, which is a function of the solar field heat loss $Q_{\text{SFHeatLoss}}$, design solar field mass flow rate $m_{\text{SFMassFlowD}}$, and the HTF specific heat at the average solar field temperature $C_{\text{pHTFatTSFAve}}$:

$$\Delta T_{\text{HTF}} = \frac{Q_{\text{SFHeatLoss}}}{m_{\text{SFMassFlowD}} \cdot C_{\text{pHTFatTSFAve}}} \tag{3.26}$$

The solar field inlet and outlet temperatures are calculated as a function of $\Delta T_{\text{HTF}}$ and $T_{\text{SFAve}}$ and an incremental value 0.001. Note that these calculations are part of the iterative repetition (shown in the flow diagram above) that stops when $T_{\text{SFout}}$ converges to within 0.1 of its value in the previous iteration.

$$T_{\text{SFin}} = T_{\text{SFAve}} + \frac{\Delta T_{\text{HTF}}}{2} + 0.001 \tag{3.27}$$

$$T_{\text{SFout}} = T_{\text{SFAve}} - \frac{\Delta T_{\text{HTF}}}{2} - 0.001 \tag{3.28}$$

For this hour, because the solar field energy is zero, the solar field load factor and mass flow rate are both set to zero:

$$F_{\text{SFLoad}} = 0 \tag{3.29}$$

$$m_{\text{SFMassFlow}} = 0 \tag{3.30}$$

## QSF is greater than zero and solar field temperature is below design point: Warm up energy required

When the initial solar field energy (calculated in Step A in the diagram) is greater than zero, and the solar field average temperature is less than the design solar field temperature, the system must warm up to reach operating temperature. SAM calculates the required warm-up energy and determines whether the solar field can provide the required energy. For systems with thermal energy storage or fossil backup, the warm-up energy can be supplied by these sources.

### Required warm-up energy E

The required warm-up energy is a function of the HTF enthalpies at the average solar field tempeatures in the current and previous hours:

$$Q_{\text{SFWarmup}} = H_{\text{HTFatTSFAveD}} - H_{\text{HTFatTSFAve0}} \cdot M_{\text{HTF}} \tag{3.31}$$

The HTF enthalpies depend on the HTF type and are calculated using the equations shown in Table 3..7.

### Solar energy for warm-up is available F

When the solar field energy is greater than the required warm-up energy, the solar field can supply the warm-up energy. The delivered solar field energy is the  initial solar field energy calculated in Step A minus the warm-up energy $Q_{\text{SFWarmup}}$, and the solar field temperatures are set to their design values.

$$Q_{\text{SF}} = Q_{\text{SF}} - Q_{\text{SFWarmup}} \tag{3.32}$$

$$T_{\text{SFAve}} = T_{\text{SFAveD}} \tag{3.33}$$

$$T_{\text{SFin}} = T_{\text{SFinD}} \tag{3.34}$$

$$T_{\text{SFout}} = 2 \cdot T_{\text{SFAve}} - T_{\text{SFin}} \tag{3.35}$$

### Solar energy for warm up is not available H

When the solar field energy is less than or equal to the required warm-up energy, there is some solar energy, but it is insufficient for warm-up. After calculating the average solar field energy based on the HTF enthalpy, SAM adjusts the required warm up energy for these new conditions, and sets the solar field energy to zero.

The average solar field temperature is set to the HTF temperature, which is a function of the HTF enthalpy in the previous hour:

$$T_{\text{SFAve}} = T_{\text{HTFatHHTF0}} \tag{3.36}$$

The HTF enthalpy in the previous hour $H_{\text{HTF0}}$ is a function of the HTF enthalpy at the previous hour's average solar field temperature $H_{\text{HTFatTSFAve0}}$, the SCA energy $Q_{\text{SCA}}$, solar field area $A_{\text{SolarField}}$, and HTF mass $M_{\text{HTF}}$:

$$H_{\text{HTF0}} = H_{\text{HTFatTSFAve0}} + \frac{Q_{\text{SCA}} \cdot A_{\text{SolarField}}}{M_{\text{HTF}}} \tag{3.37}$$

The required warm-up energy $Q_{\text{SFWarmup}}$ is calculated to account for the temperature difference between the current and previous hours and is a function of the HTF enthalpy at the average solar field temperature in the current hour $H_{\text{HTFatTSFAve}}$ and in the previous hour $H_{\text{HTFatTSFAve0}}$, and the HTF mass $M_{\text{HTF}}$:

$$Q_{\text{SFWarmup}} = (H_{\text{HTFatTSFAve}} - H_{\text{HTFatTSFAve0}}) \cdot M_{\text{HTF}} \tag{3.38}$$

The solar field energy is set to zero because no solar energy will be delivered in this hour:

$$Q_{\text{SF}} = 0 \tag{3.39}$$

The solar field inlet and outlet temperatures are calculated to account for the temperature reduction as as a function of the warm-up energy $Q_{\text{SFWarmup}}$ and design inlet and outlet temperatures:

$$T_{\mathrm{SFin}} = T_{\mathrm{SFAve}} - \frac{Q_{\mathrm{SFWarmup}}}{Q_{\mathrm{SFDesign}}} \cdot (T_{\mathrm{SFoutD}} - T_{\mathrm{SFinD}}) \tag{3.40}$$

$$T_{\mathrm{SFout}} = 2 \cdot T_{\mathrm{SFAve}} - T_{\mathrm{SFin}} \tag{3.41}$$

### QSF is greater than zero and solar field temperature is above design point: Normal operation I

During normal operation, solar field temperatures are at their design points, and the solar field energy is not modified from the initial value calculated in Step A. The required warm-up energy is also set to zero.

$$T_{\mathrm{SFAve}} = T_{\mathrm{SFAveD}} \tag{3.42}$$

$$Q_{\mathrm{SFWarmUp}} = 0 \tag{3.43}$$

$$T_{\mathrm{SFin}} = T_{\mathrm{SFinD}} \tag{3.44}$$

$$T_{\mathrm{SFout}} = 2 \cdot T_{\mathrm{SFAve}} - T_{\mathrm{SFin}} \tag{3.45}$$

### Solar field load factor and mass flow rate G

When the solar field is not in operation, the solar field load factor and mass flow rate are both set to zero.

Otherwise, when the solar field operates in either normal or warm-up mode, the solar field load factor is a function of the solar field energy $Q_{\mathrm{SF}}$ and the design solar field energy $Q_{\mathrm{SFDesign}}$, and the solar field mass flow rate $m_{\mathrm{SFMassFlow}}$ is a function of the solar field energy $Q_{\mathrm{SF}}$, and the HTF enthalpies at the solar field outlet and inlet temperatures:

$$F_{\mathrm{SFLoad}} = \frac{Q_{\mathrm{SF}}}{Q_{\mathrm{SFDesign}}} \tag{3.46}$$

$$m_{\mathrm{SFMassFlow}} = \frac{Q_{\mathrm{SF}}}{H_{\mathrm{HTFatTSFout}} - H_{\mathrm{HTFatTSFin}}} \tag{3.47}$$

## 3.8 Other Energy Quantities

In addition to the energy calculations described above, SAM calculates the values of several other energy quantities which are reported in the results and can be viewed in either the results spreadsheet (in Excel) or time series graphs (in DView). These quantities are not used in simulation calculations.

Note that unit conversion factors have been omitted from the following equations for clarity. (For example the $Q_{\mathrm{DNI}}$ value reported in the results is divided by 1,000,000 to convert from W/m$^2$ • m$^2$ to MW)

The direct normal radiation incident on the solar field $Q_{\mathrm{DNI}}$ in thermal Watts is the product of the incident solar radiation $Q_{\mathrm{NIP}}$ and the solar field area $A_{\mathrm{SolarField}}$.

$$Q_{\mathrm{DNI}} = Q_{\mathrm{NIP}} \cdot A_{\mathrm{SolarField}} \tag{3.48}$$

The radiation in the collector plane $Q_{\text{SFNipCosTh}}$ in thermal Watts:

$$Q_{\text{SFNIPCosTh}} = Q_{\text{NIP}} \cdot \cos(\theta_{\text{SolarIncidence}}) \cdot A_{\text{SolarField}} \tag{3.49}$$

The energy absorbed by the solar field before thermal losses and including optical losses $Q_{\text{SFAbs}}$ in thermal Watts

$$Q_{\text{SFAbs}} = Q_{\text{Absorbed}} \cdot A_{\text{SolarField}} \tag{3.50}$$

# 4 SCA / HCE

The SCA / HCE input variables are used to define the SCA dimensions and to calculate the SCA and HCE losses. The HCE heat losses are used by the Solar Field module in the solar field thermal energy calculations to calculate the system heat losses $Q_{\text{HeatLoss}}$. The SCA losses are used in the solar field absorbed energy equation $Q_{\text{Absorbed}}$.

## 4.1 User Input Variables

The values of input variables on the SCA / HCE page are stored in two libraries. To modify the value of a variable, the library must be edited.

### Solar Collector Assembly (SCA)

The solar collector assembly (SCA) input variables describe the dimensions and optical characteristics of the collector. The variables are stored in a library of parameters for each collector type. To change the values of these variables, you must create a new entry in the library.

**Table 4.1. SCA variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Collector Type | The name of the collector in the SCA library | | |
| SCA Length | Length of a single SCA. Used in SCA end loss calculation. | m | $D_{\text{SCALen}}$ |
| SCA Aperture | Mirror aperture of a single SCA. Used in row shadow loss and HCE heat loss calculations. | M | $D_{\text{Aperture}}$ |
| SCA Aperture Area | Area of aperture of single SCA. Not used. | $m^2$ | $A_{\text{Aperture}}$ |
| Average Focal Length | Average trough focal length. Used in end gain and end loss calculations. | m | $D_{\text{AvgFocalLen}}$ |
| # of Receivers/SCA | Number of HCEs per SCA. Not used. | | $N_{\text{HCEperSCA}}$ |
| Incident Angle Modifier - Coeff 1...3 | Incident angle modifier coefficients. Used to calculate incident angle modifier factor. | | $F_{\text{IAM}}$ |
| Tracking Error and Twist | Error factor that accounts for tracking error and | | $F_{\text{TrackTwist}}$ |
| Geometric Accuracy | Used to calculate SCA field error. | | $F_{\text{GeomAccuracy}}$ |
| Mirror Reflectivity | Used to calculate SCA field error. | | $F_{\text{MirrorRefl}}$ |
| Mirror Cleanliness Factor (field avg) | Used to calculate SCA field error. | | $F_{\text{MirrorClean}}$ |
| Dust on Envelope (field avg) | Used to calculate HCE field error. | | $F_{\text{DustEnvelope}}$ |
| Concentrator Factor | Used to calculate SCA field error. | | $F_{\text{Concentrator}}$ |
| Solar Field Availability | Used to calculate absorbed energy $Q_{\text{Absorbed}}$. | | $F_{\text{SFAvailability}}$ |

## Receiver / Heat Collection Element (HCE)

The HCE variables describe the properties of up to four HCE types that can make up the solar field. This makes it possible to model a solar field with HCEs in different states. Each set of properties applies to one of the HCE types. The Percent of Field variable determines what portion of the solar field is made up of a given HCE type.

**Table 4.2. HCE variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Receiver type and condition | The name of the receiver and its condition. Vacuum refers to an HCE in good condition, lost vacuum, broken glass, and hydrogen refer to different problem conditions. | -- | -- |
| Percent of Field | Fraction of solar field using this HCE type and condition. Used to calculate HCE field error and HCE heat loss. | -- | $F_{\mathrm{HCEField}}$ |
| Bellows Shadowing | Used to calculate HCE field error. | -- | $F_{\mathrm{BellowsShading}}$ |
| Envelope Transmissivity | Used to calculate HCE field error. | -- | $F_{\mathrm{EnvTrans}}$ |
| Absorber Absorbtion | This factor accounts for inefficiencies in the HCE black coating. Used to calculate HCE field error. | -- | $F_{\mathrm{Absorption}}$ |
| Unaccounted | HCE loss factor used for miscellaneous losses not covered by other factors. Used to calculate HCE field error. | -- | $F_{\mathrm{Unaccounted}}$ |
| Optical Efficiency (HCE) | This value is provided for reference on the SCA / HCE page. SAM calculates the HCE optical efficiency for each hour during simulation based on the loss factors on the SCA / HCE page and the incident angle modifier factor with depends on the time of day and collector orientation. | -- | -- |
| Optical Efficiency (Weighted) | This value is provided for reference on the SCA / HCE page. SAM calculates the HCE optical efficiency for each hour during simulation based on the loss factors on the SCA / HCE page and the incident angle modifier factor with depends on the time of day and collector orientation. | -- | -- |
| Heat Loss Coefficient A0...A6 | Used to calculated the HCE heat loss. | -- | $F_{\mathrm{HL0...6}}$ |
| Heat Loss Factor | Performance factor that applies to this HCE type and condition. Used to calculated HCE heat loss. | -- | $F_{\mathrm{HeatLoss}}$ |
| Minimum Windspeed (m/s) | Used to calculated the HCE heat loss for hours when the wind speed from the weather file is lower than the minimum wind speed. | m/s | -- |
| Receiver Heat Losses (W/m)<br>Thermal Losses (Weighted W/m)<br>Thermal Losses (Weighted W/m2) | These values are provided for reference on the SCA / HCE page. SAM calculates the HCE heat loss for each hour during simulation based on the loss factor coefficients on the SCA / HCE page and other values from the weather file. | W/m, W/m$^2$ | -- |

# 4.2 SCA Losses

The SCA (Collector) losses consist of end loss, row shadowing loss, and optical loss.

## End loss

The SCA end losses result from light that reflects off the end of each SCA. The end loss factor $F_{\mathrm{EndLoss}}$ depends on the SCA average focal length $D_{\text{SCAFocalLength}}$, the solar incidence angle $\theta_{\text{SolarIncidence}}$, and the number of SCAs per row, $N_{\text{SCAperRow}}$ from the Solar Field page.

$$F_{\text{EndLoss}} = 1 - \frac{D_{\text{SCAAvgFocalLength}} \cdot \tan(\theta_{\text{SolarIncidence}}) - \frac{(N_{\text{SCAperRow}} - 1)}{N_{\text{SCAperRow}} \cdot F_{\text{EndGain}}}}{D_{\text{SCALength}}} \tag{4.1}$$

The end gain factor $F_{\text{EndGain}}$ accounts for small gains in solar input from light reflecting off of neighboring SCA ends.

$$F_{\text{EndGain}} = D_{\text{SCAFocalLength}} \cdot \tan(\theta_{\text{SolarIncidence}}) - D_{\text{DistanceBetweenSCAsInRow}} \tag{4.2}$$

### Shadowing loss

The SCA shadowing losses result from row-to-row shadowing that occurs shortly after sunrise and shortly before sunset. The row to row shadowing losses factor is a function of the collector angle, distance between SCAs in a row, and the SCA aperture length.

$$F_{\text{RowShadow}} = \left| \sin\left(\frac{\pi}{2} - \theta_{\text{Track}}\right) \cdot \frac{L_{\text{DistanceBetwenSCAsInRow}}}{L_{\text{SCAApertureLength}}} \right| \tag{4.3}$$

### Optical efficiency

The SCA optical efficiency factor is the produced of the HCE and SCA field error factors:

$$F_{\text{SCAOptEff}} = F_{\text{SCAFieldError}} \cdot F_{\text{HCEFieldError}} \tag{4.4}$$

The SCA field error factor is a function of the efficiency factors on the SCA / HCE page, Tracking Error and Twist, Geometric Accuracy, Mirror Reflectivity, Mirror Cleanliness Factor and Concentrator Factor. (Note that the Dust on Envelope factor is used for the HCE field error calculation, not here.)

$$F_{\text{SCAFieldError}} = F_{\text{TrackTwist}} \cdot F_{\text{GeomAcc}} \cdot F_{\text{MirrRefl}} \cdot F_{\text{MirrClean}} \cdot F_{\text{Concentrator}} \tag{4.5}$$

The HCE field error factor is the sum of HCE field error factors for each HCE type on the SCA / HCE page. The error factor for a single HCE type is:

$$F_{\text{HCEFieldError}} = F_{\text{PercentOfField}} \cdot F_{\text{Dust}} \cdot F_{\text{Bellows}} \cdot F_{\text{Transmissivity}} \cdot F_{\text{Absorption}} \cdot F_{\text{Unaccounted}} \tag{4.6}$$

## 4.3 HCE Losses

The HCE (receiver) heat loss is a function of the seven heat loss coefficients on the SCA / HCE page, and wind speed, solar field inlet and outlet temperatures, ambient temperature, insolation, and collector angle. The wind speed used for the heat loss calculation, $v_{\text{Wind}}$, is the larger of the minimum wind speed variable on the SCA / HCE page and the average hourly wind speed from the weather data file.

The adjusted HCE heat loss in Watts per square meter of HCE aperture is:

$$Q_{\text{HCELoss}} = \frac{Q_{\text{HCEHLTotal}} \cdot F_{\text{HeatLoss}} \cdot F_{\text{PercentOfField}}}{D_{\text{MirrorAperture}}} \tag{4.7}$$

SAM repeats this calculation for each of the four HCE types defined on the SCA / HCE page to calculate the solar field heat loss due to HCE performance and efficiency.

The total heat loss in Watts per meter of SCA length is the sum of the four HCE heat loss terms divided by the difference between the solar field outlet and inlet temperatures:

$$Q_{\mathrm{HCEHLTotal}} = \frac{Q_{\mathrm{HCEHL1}} + Q_{\mathrm{HCEHL2}} + Q_{\mathrm{HCEHL3}} + Q_{\mathrm{HCEHL4}}}{T_{\mathrm{TSFout}} - T_{\mathrm{TSFin}}} \tag{4.8}$$

The four HCE heat loss terms $Q_{\mathrm{HCEHL1}}$, $Q_{\mathrm{HCEHL2}}$, $Q_{\mathrm{HCEHL3}}$, and $Q_{\mathrm{HCEHL4}}$ are calculated as follows:

$$Q_{\mathrm{HCEHL1}} = \left(F_{\mathrm{HLA0}} + F_{\mathrm{HLA5}} \cdot \sqrt{\upsilon_{\mathrm{Wind}}}\right) \cdot \left(T_{\mathrm{SFout}} - T_{\mathrm{SFin}}\right) \tag{4.9}$$

$$Q_{\mathrm{HCEHL2}} = \frac{F_{\mathrm{HLA1}} + F_{\mathrm{HLA6}} \cdot \sqrt{\upsilon_{\mathrm{Wind}}}}{2} \cdot \left[\left(T_{\mathrm{SFout}}{}^{2} - T_{\mathrm{SFin}}{}^{2}\right) - T_{\mathrm{Amb}} \cdot \left(T_{\mathrm{SFout}} - T_{\mathrm{SFin}}\right)\right] \tag{4.10}$$

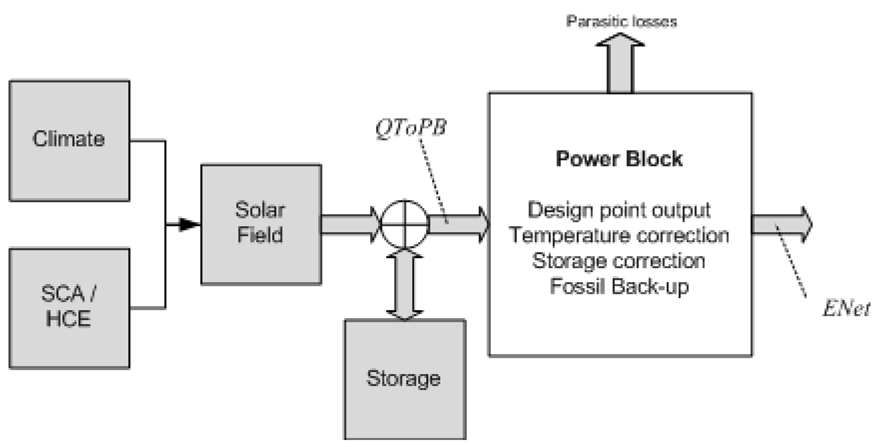
$$Q_{\mathrm{HCEHL3}} = \frac{F_{\mathrm{HLA2}} + F_{\mathrm{HLA4}} \cdot Q_{\mathrm{NIP}} \cdot \cos(\theta_{\mathrm{SolarIncidence}}) \cdot F_{\mathrm{IAM}}}{3} \cdot \left(T_{\mathrm{SFTout}}{}^{3} - T_{\mathrm{SFTin}}{}^{3}\right) \tag{4.11}$$

$$Q_{\mathrm{HCEHL4}} = \frac{F_{\mathrm{HLA3}}}{4} \cdot \left(T_{\mathrm{SFTout}}{}^{4} - T_{\mathrm{SFTin}}{}^{4}\right) \tag{4.12}$$

# 5 Power Block

The power block module calculates the hourly net electric output $E_{\mathrm{Net}}$ based on the energy supplied to the power block $Q_{\mathrm{ToPB}}$ calculated by the Storage and Dispatch module.

**Figure 5.1. Diagram of the power block module**




The power block module first calculates the design point gross electric output, then applies a series correction factors, and adds energy from the fossil back-up system, and subtracts parasitic losses:

1. Calculate the design point gross electric output originating from solar energy $E_{\mathrm{GrossSolarDesign}}$.
2. Calculate the temperature-corrected gross electric output $E_{\mathrm{GrossSolarTempCorr}}$.
3. If the system employs a thermal energy storage system, calculate the storage-corrected gross electric output, $E_{\mathrm{GrossSolarTES}}$.
4. Add any energy from fossil backup to calculate the gross turbine generation $E_{\mathrm{GrossTurbine.}}$
5. Subtract parasitic losses due to electric loads through the system to calculate the net electric generation $E_{\mathrm{Net}}$.

## 5.1 User Input Variables

The user inputs on the Power Block page are divided into two groups, the Turbine Ratings group and the Power Cycle group.

### Turbine ratings

The turbine ratings variables determine the steam turbine's capacity, availability, and degradation rate. SAM models the power block's steam turbine based on a reference steam turbine from the built-in library. The reference turbine parameters determine the steam turbine's performance characteristics, and the turbine rating variables determine the steam turbine's capacity, availability, and annual degradation rate.

**Table 5.1. Turbine rating input variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Rated Turbine Net Capacity | Nameplate capacity of turbine. SAM does not use this variable in energy calculations, but does use it as the system capacity in the economic calculations. | MWe | -- |
| Design Turbine Gross Output | Gross electric output of turbine, typically 110% of rated turbine net capacity. Used to calculate design turbine thermal input. | MWe | $E_{\mathrm{Design}}$ |
| Power Plant Availability | Fraction of net electric energy generated by the power block that is delivered to the grid. | | $F_{\mathrm{PBAvailability}}$ |
| Annual Degradation | Annual reduction in power block output. | | $F_{\mathrm{Degradation}}$ |

### Power cycle

The power cycle variables describe a reference steam turbine. SAM uses the reference turbine specifications to calculate the turbine output, and then scales the actual output based on the turbine rating variables. Each set of reference turbine specifications is stored in the reference steam turbine library.

**Table 5.2. Power cycle input variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Ref System | Name of the reference turbine. Selecting a reference system determines the values of the other power cycle variables. | -- | -- |
| System Type | Brief description of the reference turbine. Does not affect calculations. | -- | -- |
| Design Turbine Thermal Input | Thermal energy required as input to the reference turbine to generate the design turbine gross electric output. It is the design turbine gross output divided by the design turbine gross efficiency. | MWt | $Q_{\mathrm{PBDesign}}$ |
| Design Turbine Gross Efficiency | Total thermal to electric efficiency of the reference turbine. Used to calculate the design turbine thermal input. | -- | $F_{\mathrm{GrossTurbineEffD}}$ |
| Max Over Design Operation | The turbine's maximum output expressed as a fraction of the design turbine thermal input. Used by the dispatch module. | -- | $F_{\mathrm{PBMax}}$ |
| Minimum Load | The turbine's minimum load expressed as a fraction of the design turbine thermal input.Used by the dispatch module. | -- | $F_{\mathrm{PBMin}}$ |
| Turbine Start-up Energy | Factor used to calculated the thermal energy requirement during start-up. Used by the dispatch module. | -- | $F_{\mathrm{StartUp}}$ |
| Boiler LHV Efficiency | Boiler lower heating value efficiency. Used to calculate backup fossil fuel energy use. | -- | $LHV$ |
| Turb. Part Load Therm to Elec | Factors for turbine thermal to electric efficiency under part load polynomial equation. Used to calculate the turbine's electric output. | -- | $F_{\mathrm{TE}}$ |
| Turb. Part Load Elec to | Factors for turbine's part load electric to thermal efficiency | -- | $F_{\mathrm{ET}}$ |

| Name | Description | Units | Symbol |
|---|---|---|---|
| Therm | polynomial equation. Used to calculate the energy required of the back up fossil system. | | |
| Cooling Tower Correction | Factors to calculate the temperature correction factor to represent cooling tower losses. To model a system with no cooling tower correction, set F0 to 1, and F1 = F2 = F3 = F4 =0. | -- | $F_{\mathrm{TC}}$ |
| Temperature Correction Mode | Wet bulb mode uses the wet bulb temperature from the weather data set to calculate the temperature correction factor. Dry bulb mode uses the ambient temperature. | -- | -- |

## 5.2 Design Point Gross Output

The design point gross electric output $E_{\mathrm{GrossSolarDesign}}$ is the electric output of the power block at the design thermal input $Q_{\mathrm{PBDesign}}$. SAM uses the gross electric output as a starting point in the calculation of the system's hourly electricity output, applies correction factors as appropriate for the cooling and storage systems, and ensures that the output values do not exceed the limits allowed by the minimum and maximum load factors defined by the inputs on the Power Block page.

The design point gross electric output is a function of the turbine's design turbine gross output $E_{\mathrm{Design}}$ on the Power Block page and the normalization factor $F_{\mathrm{Norm}}$:

$$E_{\mathrm{GrossSolarDesign}} = E_{\mathrm{Design}} \cdot F_{\mathrm{Norm}} \tag{5.1}$$

The normalization factor $F_{\mathrm{Norm}}$ is a function of hourly thermal energy delivered to the power block $Q_{\mathrm{ToPB}}$ calculated by the Dispatch and Storage module, the design turbine thermal input variable $Q_{\mathrm{PBDesign}}$ on the Power Block page, and the steam turbine part load thermal to electric efficiency coefficients, $F_{\mathrm{TE0}}$ through $F_{\mathrm{TE4}}$, which are the user-defined coefficients on the Power Block page:

$$\begin{aligned} F_{\mathrm{Norm}} = F_{\mathrm{TE4}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}}\right)^4 + F_{\mathrm{TE3}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}}\right)^3 + \\ F_{\mathrm{TE2}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}}\right)^2 + F_{\mathrm{TE1}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}}\right) + F_{\mathrm{TE0}} \end{aligned} \tag{5.2}$$

The design turbine thermal input $Q_{\mathrm{PBDesign}}$ shown on the Power Block page is the quotient of the two Power Block page inputs, the design turbine gross output $E_{\mathrm{Design}}$ and the design turbine gross efficiency $F_{\mathrm{GrossTurbineEffD}}$:

$$Q_{\mathrm{PBDesign}} = \frac{E_{\mathrm{Design}}}{F_{\mathrm{GrossTurbineEffD}}} \tag{5.3}$$

## 5.3 Correction Factors

After calculating the design point gross output $E_{\mathrm{GrossSolarDesign}}$, SAM corrects the value to account for conversion efficiencies associated with the cooling towers and TES system by applying temperature and TES correction factors. The corrected gross output $E_{\mathrm{GrossSolarCorr}}$ is a function of $E_{\mathrm{GrossSolarDesign}}$ and the two correction factors

$F_{\mathrm{CorrTemp}}$ and $F_{\mathrm{CorrTES}}$:

$$E_{\mathrm{GrossSolarCorr}} = E_{\mathrm{GrossSolarDesign}} \cdot F_{\mathrm{CorrTemp}} \cdot F_{\mathrm{CorrTES}} \tag{5.4}$$

### Temperature Correction

The temperature correction factor $F_{\mathrm{TempCorr}}$ is calculated based on whether the power block employs wet or dry cooling. and is a function of the temperature $T_{\mathrm{TC}}$ and the five cooling tower correction factors $F_{\mathrm{TC0}}$ through $F_{\mathrm{TC4}}$ on the Power Block page:

$$F_{\mathrm{TempCorr}} = F_{\mathrm{TC4}} \cdot T_{\mathrm{TC}}{}^{4} + F_{\mathrm{TC3}} \cdot T_{\mathrm{TC3}}{}^{3} + F_{\mathrm{TC2}} \cdot T_{\mathrm{TC2}}{}^{2} + F_{\mathrm{TC1}} \cdot T_{\mathrm{TC1}} + F_{\mathrm{TC0}} \tag{5.5}$$

$T_{\mathrm{TC}}$ is either the wet bulb temperature or the ambient temperature for the given hour in the weather data set. When the temperature correction mode on the Power Block page is "wetbulb basis," $T_{\mathrm{TC}}$ is equal to the wet bulb temperature. When the mode is "drybulb basis," $T_{\mathrm{TC}}$ is the dry bulb temperature.

### TES Correction

The thermal energy storage correction factor $F_{\mathrm{CorrTES}}$ is a function of the energy delivered by the TES $Q_{\mathrm{fromTES}}$ and energy delivered to the power block $Q_{\mathrm{toPB}}$ calculated by the Dispatch and Storage module, and the turbine TES adjustment efficiency $F_{\mathrm{TESAdjustEfficiency}}$ from the Storage page:

$$F_{\mathrm{CorrTES}} = \left(1 - \frac{Q_{\mathrm{FromTES}}}{Q_{\mathrm{ToPB}}}\right) + \frac{Q_{\mathrm{FromTES}}}{Q_{\mathrm{ToPB}}} \cdot F_{\mathrm{TESAdjustEfficiency}} \tag{5.6}$$

Note that for a system with no TES, $Q_{\mathrm{fromTES}}$ is zero, and the correction factor is one.

## 5.4 Gross Solar Output

After calculating the corrected gross solar output $E_{\mathrm{GrossSolarCorr}}$, SAM checks to ensure that the value does not fall below the minimum load $E_{\mathrm{GrossSolarMin}}$ or exceed the maximum over design operation $E_{\mathrm{GrossSolarMax}}$.

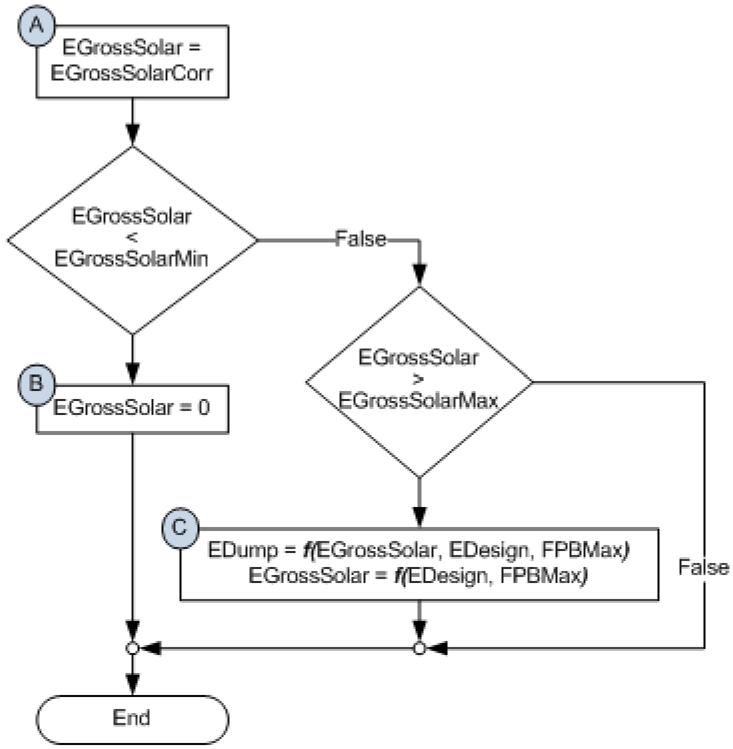
$E_{\mathrm{GrossSolarMin}}$ is a function of the design turbine gross output $E_{\mathrm{Design}}$ and the minimum load factor $F_{\mathrm{PBMin}}$ on the Power Block page:

$$E_{\mathrm{GrossSolarMin}} = E_{\mathrm{Design}} \cdot F_{\mathrm{PBMin}} \tag{5.7}$$

$E_{\mathrm{GrossSolarMax}}$ is a function of the design turbine gross output $E_{\mathrm{Design}}$ and the maximum over design operation factor $F_{\mathrm{PBMax}}$ on the Power Block page:

$$E_{\mathrm{GrossSolarMax}} = E_{\mathrm{Design}} \cdot F_{\mathrm{PBMax}} \tag{5.8}$$

**Fig 5.2. Diagram of the gross solar output limits algorithm**




## Initial gross solar output A

The inital value of the gross electric generation from solar energy $E_{\text{GrossSolar}}$ is the corrected gross solar ouptut $E_{\text{GrossSolarCorr}}$:

$$E_{\text{GrossSolar}} = E_{\text{GrossSolarCorr}} \tag{5.9}$$

## Solar energy is energy insufficient to drive turbine B

For hours when the resulting $E_{\text{GrossSolar}}$ is not sufficient to drive the turbine, SAM stores the value $E_{\text{Min}}$ which is reported in the hourly results:

$$E_{\text{Min}} = E_{\text{GrossSolar}} \tag{5.10}$$

and then sets the gross solar output to zero:

$$E_{\text{GrossSolar}} = 0 \tag{5.11}$$

## Solar energy exceeds maximum turbine output limits C

For hours when $E_{\text{GrossSolar}}$ exceeds the energy required to drive the turbine at is maximum design gross output rating, the turbine produces excess electricity $E_{\text{Dump}}$:

$$E_{\text{Dump}} = E_{\text{GrossSolar}} - E_{\text{Design}} \cdot F_{\text{PBMax}} \tag{5.12}$$

and the gross solar output is set to its maximum value:

$$E_{\text{GrossSolar}} = E_{\text{GrossSolarMax}} \tag{5.13}$$

## 5.5 Fossil Back-up

The fossil backup module calculates the thermal energy from the fossil fuel-fired boiler $Q_{\text{Gas}}$ and electric generation from the boiler $E_{\text{GrossFossil}}$. These calculations use the fossil fill fraction for the current hour, which is determined by the table of fossil fill fraction values on the Storage page and the TOU schedule on the Utility Rates page. The TOU schedule determines which period (1 through 6) applies to the current hour, and the fossil fill table determines which fossil fill fraction applies to each period.

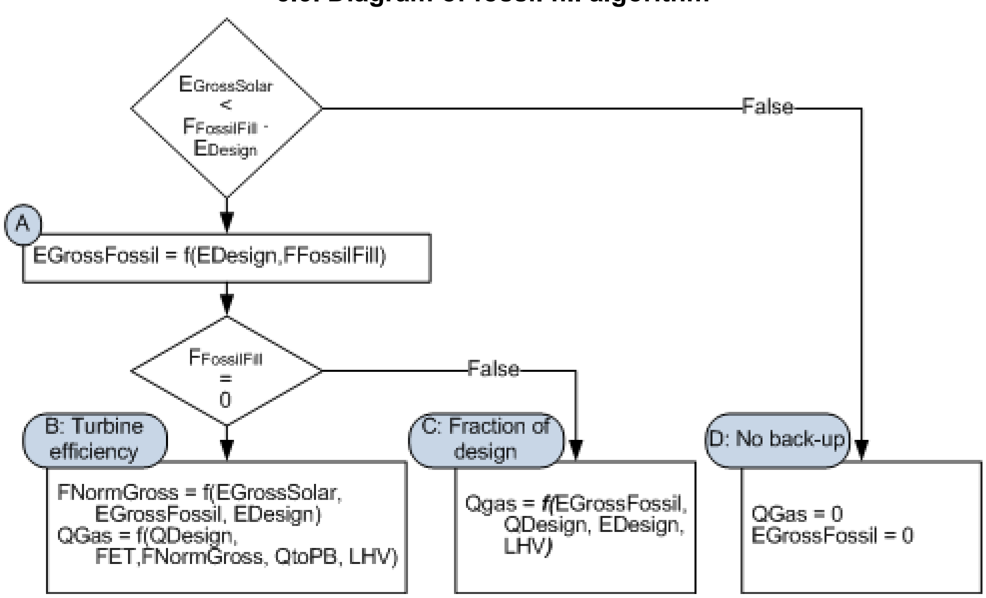
The relationship between the design fossil fraction and solar field energy determines whether the boiler supplies energy to the turbine. The design fossil fraction is the product of $E_{\text{GrossSolar}}$ and the fossil fill fraction on the Storage page for the current hour. When the gross solar output is greater than or equal to the design fossil fraction, there is no energy from the boiler. When the gross solar output is less than the design fossil fraction, SAM first calculates the gross fossil electric output $E_{\text{GrossFossil}}$ as a function of the design turbine gross output $E_{\text{Design}}$ and the fossil fill fraction for the current hour, and then determines the thermal energy from fuel $Q_{\text{Gas}}$ required to generate the electricity.

When the fossil fill fraction is zero, $Q_{\text{Gas}}$ is a function of the turbine's power curve. Otherwise, it is a function of the design turbine gross output.

The fossil back-up equations use the following variables:

- Gross solar output $E_{\text{GrossSolar}}$
- Fossil fill fraction $F_{\text{FossilFill}}$ and time of use schedule
- Design turbine gross output $E_{\text{Design}}$
- Design turbine thermal input $Q_{\text{Design}}$
- Electric to thermal efficiency factors $F_{\text{ET0}}$, $F_{\text{ET1}}$, $F_{\text{ET2}}$, $F_{\text{ET3}}$, $F_{\text{ET4}}$
- Boiler lower heating value $LHV$

**5.3. Diagram of fossil fill algorithm**



## Gross electric generation from the boiler A

The gross electric generation required from the boiler $E_{\text{GrossFossil}}$ is the fraction of the design turbine gross output $E_{\text{Design}}$ determined by the user-defined fossil fill fraction less solar energy available from the solar field and thermal energy storage:

$$E_{\text{GrossFossil}} = E_{\text{Design}} \cdot F_{\text{FossilFill}} - E_{\text{GrossSolar}} \tag{5.14}$$

## Fuel calculated as a function of turbine power curve B

When the fossil fill fraction for the current hour is zero, the fossil fuel energy required to generate the gross electric generation from the boiler $Q_{\text{Gas}}$ is calculated using the turbine's part load efficiency factors. It is a function of the normalization factor $F_{\text{NormGross}}$, the design gross turbine thermal input $Q_{\text{PBDesign}}$ adjusted by the five turbine part load efficiency factors $F_{\text{ET0}}$ ... $F_{\text{ET4}}$, thermal energy delivered to the power block $Q_{\text{toPB}}$ (calculated by the Dispatch and Storage module), and the boiler lower heating value efficiency $LHV$:

$$Q_{\text{Gas}} = \frac{Q_{\text{PBDesign}} \cdot C - Q_{\text{ToPB}}}{\text{LHV}} \tag{5.15}$$

$$\begin{aligned} C = {} & F_{\text{ET4}} \cdot F_{\text{NormGross}}{}^{4} + F_{\text{ET3}} \cdot F_{\text{NormGross}}{}^{3} + \\ & F_{\text{ET2}} \cdot F_{\text{NormGross}}{}^{2} + F_{\text{ET1}} \cdot F_{\text{NormGross}} + F_{\text{ET0}} \end{aligned} \tag{5.16}$$

The normalization factor $F_{\text{NormGross}}$ is a function of the gross solar output $E_{\text{GrossSolar}}$, gross boiler output $E_{\text{GrossFossil}}$, and the design gross turbine electrical output $E_{\text{Design}}$:

$$F_{\text{NormGross}} = \frac{E_{\text{GrossSolar}} + E_{\text{GrossFossil}}}{E_{\text{Design}}} \tag{5.17}$$

## Fuel calculated as a fraction of the design point C

When the fossil fill fraction is not zero, the required fossil fill energy $Q_{\text{Gas}}$ is a function of the unadjusted design gross turbine output $Q_{\text{PBDesign}}$, boiler lower heating value efficiency $LHV$, the gross electric generation from the boiler $E_{\text{GrossFossil}}$, and the design gross turbine electrical output $E_{\text{Design}}$:

$$Q_{\text{Gas}} = \frac{E_{\text{GrossFossil}} \cdot Q_{\text{PBDesign}}}{E_{\text{Design}} \cdot \text{LHV}} \tag{5.18}$$

## No energy required from the boiler D

For hours when the gross solar energy is less than the  fraction of the design gross turbine output that is the fossil fill requirement, $Q_{\text{Gas}}$ and $E_{\text{GrossFossil}}$ are both zero.

$$Q_{\text{Gas}} = 0 \tag{5.19}$$

$$E_{\text{GrossFossil}} = 0 \tag{5.20}$$

### Heater load factor

The heater (boiler) load factor is a function of the gross electric generation from fossil EGrossFossil and the design gross turbine electrical output $E_{\text{Design}}$:

$$F_{\text{HtrLoad}} = \frac{E_{\text{GrossFossil}}}{E_{\text{Design}}} \tag{5.21}$$

The heater load factor is used in the parasitic loss calculations.

## 5.6 Electric Generation

### Gross electric generation

The gross electric generation $E_{\text{GrossTurbine}}$ is the total electric generation from solar and fossil sources not accounting for parasitic losses:

$$E_{\text{GrossTurbine}} = E_{\text{GrossFossil}} + E_{\text{GrossSolar}} \tag{5.22}$$

### Power block load factor

The power block load factor is a function of the gross electric generation $E_{\text{GrossTurbine}}$ and the design turbine gross output $E_{\text{Design}}$:

$$F_{\text{PBLoad}} = \frac{E_{\text{GrossTurbine}}}{E_{\text{Design}}} \tag{5.23}$$

The power block load factor is used in the parasitic loss calculations described in the Parasitics chapter.

### Hourly net electric generation

The hourly net electric output $E_{\text{Net}}$ is a function of the gross turbine output $E_{\text{GrossTurbine}}$ and the parasitic losses $E_{\text{Parasitics}}$ (described in the Parasitics chapter):

$$E_{\text{Net}} = E_{\text{GrossTurbine}} - E_{\text{Parasitics}} \tag{5.24}$$

### Annual net electric generation

SAM calculates the net electric annual output for the system's first year of production by adding the 8,760 hourly net output values, where $h$ is the hour of the year, and $E_{\text{Net,h}}$ is the net hourly output for that hour:

$$E_{\text{NetYearOne}} = \sum_{h=1}^{8760} E_{\text{Net,h}} \tag{5.25}$$

### Annual delivered electric generation

The delivered annual output in year one $E_{\text{DeliveredYearOne}}$ is the net annual output multiplied by the power plant availability factor $F_{\text{Availability}}$ on the Power Block page:

$$E_{\mathrm{DeliveredYearOne}} = E_{\mathrm{NetYearOne}} \cdot F_{\mathrm{Availability}} \tag{5.26}$$

To calculate the output values in year two and subsequent years used for economic calculations, SAM uses the following equation, where $F_{\mathrm{Degradation}}$ is the annual degradation on the Power Block page, and $y$ is the year:

$$E_{\mathrm{DeliveredAnnual,y}} = E_{\mathrm{DeliveredYearOne}} \cdot \left(1 - F_{\mathrm{Degradation}}\right)^{y-1} \tag{5.27}$$

# 6 Dispatch and Storage

The dispatch and storage module performs two functions:

- Determine how energy is dispatched from the solar field, to and from thermal energy storage (TES), and to the power block.
- Model the TES system for systems with storage.

The dispatch mode depends on the power block operating mode, the amount of energy available from the solar field (and TES, if available), and the energy required by the power block. The power block has three operating modes:

- Not operating
- Starting up
- Operating

SAM assumes that the power block is not operating in the first hour of simulation, and then determines the operating mode for subsequent hours based on the operating mode of the previous hour and energy available from the solar field. For systems with storage, the operating mode also depends on the energy available from the TES and its state of charge.

For each hour of simulation, SAM calculates the energy delivered to the power block, which may come from the solar field, or from both the solar field and TES for systems with storage. Note that energy from a back-up fossil fuel-fired boiler is calculated separately by the Power Block module. For hours when the solar field energy exceeds the energy required by the power block (the design turbine gross output on the Power Block page), the excess solar energy is delivered to the TES. If the TES is full or the available solar energy exceeds the TES charge capacity, the remaining thermal energy is dumped.

## 6.1 User Input Variables

The user inputs on the Storage page are divided into two groups: Thermal energy storage (TES) and thermal storage dispatch controls. The dispatch and storage module also uses inputs from the Power Block page, and the TOU schedule on the Utility Rates page, which determines the hour of the year for each of the six TOU periods.

Equations for calculated values in the following tables are described in the Dispatch Parameters section below.

### Thermal Energy Storage (TES)

**Table 6.1. Thermal energy storage (TES) input variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Equiv. Full Load Hours of TES | The thermal storage capacity expressed in hours. The physical capacity is the number of hours of storage multiplied by the power block design thermal input. | hours | $N_{\mathrm{HoursofStorage}}$ |

| Name | Description | Units | Symbol |
|---|---|---|---|
| Thermocline or Two-Tank TES | A thermocline storage system consists of a single tank with a top layer of hot storage fluid and bottom layer of cold storage fluid with sand and quartzite as filler material. A two-tank system consists of a cold storage tank and hot storage tank. This variable is not active in the current version of SAM. | - | - |
| Storage Fluid Number | Storage fluid used in the TES. When the storage fluid and solar field HTF are different, the system is an indirect system with a heat exchanger. When the storage fluid and HTF are the same, the system is a direct system that uses the solar field HTF as the storage medium. Used to calculate the heat exchanger duty. | - | - |
| Maximum Energy Storage | The thermal energy storage capacity of the TES. | MWht | $Q_{\text{inTESMax}}$ |
| Design Turbine Thermal Input | The thermal input requirement of the power block to operate at its design point. From the Power Block page. | MWt | $Q_{\text{PBDesign}}$ |
| Initial Thermal Storage | Energy in storage tank during first hour of simulation. Not used. | MWht | None |
| Tank Heat Losses | Thermal losses from the storage tank. This value is subtracted from the total energy in storage at the end of each simulation hour. | MWt | $Q_{\text{TankHeatLoss}}$ |
| Heat Exchanger Duty | Applies only to systems that use a different storage fluid and solar field HTF. Used to calculate the maximum TES charge and discharge rates. | None | $F_{\text{HeatExchangerDuty}}$ |
| Turbine TES - Adj. - Efficiency | Efficiency adjustment factor. Used to calculate maximum TES charge and discharge rates. Also used by the Power Block module for the TES correction factor. | None | $F_{\text{TESAdjustEfficiency}}$ |
| Turbine TES Adjustment - Gross Output | Efficiency adjustment factor. Used to calculate maximum TES charge and discharge rates. | None | $F_{\text{TESAdjustOutput}}$ |
| Maximum Power to Storage | Maximum TES charge rate. | MWt* | $Q_{\text{toTESMax}}$ |
| Maximum Power From Storage | Maximum TES discharge rate. | MWt* | $Q_{\text{fromTESMax}}$ |
| Primary bed material<br>Secondary bed material<br>Thermocline Temp Degradation<br>Thermocline Efficiency Adj for TES<br>Thermocline Output Adj for TES | These variables apply to thermocline storage systems and are not active in the current version of SAM. | | |

*Note that although these values are rates with units of MWh/h, they are used in equations with energy values in units of MWh because the rate values are all averaged over a one hour period, and therefore have units of MWh/h x 1 h.

## Storage Dispatch Controls

The storage dispatch control variables each have six values, one for each TOU period. They determine which set of equations are used to calculate the energy flows between the solar field, TES, and power block. Note that although the fossil fill fraction is included on the Storage page, it is used by the Power block module.

**Table 6.2. Thermal energy storage (TES) input variables**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Storage Dispatch Fraction (with Solar) | The fraction of energy in the TES required for the system to start when the solar field energy is greater than zero. This applies only when the system did not operate in the previous hour. | None | $F_{\text{WithSolar}}$ |
| Storage Dispatch Fraction (without Solar) | The fraction of energy in the TES required for the system to start when the solar field energy is equal to zero. This applies only when the system did not operate in the previous hour. | None | $F_{\text{WithoutSolar}}$ |
| Turbine Output Fraction | The fraction of the design turbine thermal input adjusted by the turbine part load electric to thermal efficiency factors. Used to calculate the power block load requirement. | None | $F_{\text{PBOut}}$ |
| Fossil Fill Fraction | Fraction of the power block design turbine gross output that can be met by the back-up boiler. Used by the Power Block module. | None | $F_{\text{FossilFill}}$ |

### Utility Rates

The schedules on the utility rates page determine when each of the six TOU periods apply during the year. Each TOU period applies to a given hour of the day for an entire month. The TOU periods determine how energy is dispatched and how the fossil fuel-fired boiler is operated.

## 6.2 Dispatch Parameters

The dispatch parameters variables that ensure that calculated energy values stay within defined limits and requirements.

### Power block input limits

The energy to the power block $Q_{\text{toPB}}$ is limited by the maximum input $Q_{\text{toPBMax}}$ and minimum input $Q_{\text{toPBMin}}$, which are determined by the maximum over design operation value $F_{\text{PBMax}}$ and minimum load value $F_{\text{PBMin}}$ respectively. QtoPB is also a function of the design turbine thermal input $Q_{\text{PBDesign}}$ and the five turbine part load electric to thermal efficiency factors $F_{\text{ET0}}$ ... $F_{\text{ET4}}$ on the Power Block page:

$$Q_{\text{toPBMin}} = Q_{\text{PBDesign}} \cdot \left(F_{\text{ET4}} \cdot F_{\text{PBMin}}{}^4 + F_{\text{ET3}} \cdot F_{\text{PBMin}}{}^3 + F_{\text{ET2}} \cdot F_{\text{PBMin}}{}^2 + F_{\text{ET1}} \cdot F_{\text{PBMin}} + F_{\text{ET0}}\right) \quad (6.1)$$

$$Q_{\text{toPBMax}} = Q_{\text{PBDesign}} \cdot \left(F_{\text{ET4}} \cdot F_{\text{PBMax}}{}^4 + F_{\text{ET3}} \cdot F_{\text{PBMax}}{}^3 + F_{\text{ET2}} \cdot F_{\text{PBMax}}{}^2 + F_{\text{ET1}} \cdot F_{\text{PBMax}} + F_{\text{ET0}}\right) \quad (6.2)$$

### Power block load requirement

The power block load requirement for each hour $Q_{\text{PBLoad}}$ is a function of the turbine output fraction values $F_{\text{PBOut}}$ on the Storage page, the design turbine thermal input $Q_{\text{PBDesign}}$ on the power block page, and the TOU schedule on the Utility Rates page. Each hour of the year is assigned to a single TOU period on the TOU schedule, and each of the six TOU periods has a different load requirement.

$$Q_{\text{PBLoad}} = Q_{\text{PBDesign}} \cdot \left(F_{\text{ET4}} \cdot F_{\text{PBOut}}{}^{4} + F_{\text{ET3}} \cdot F_{\text{PBOut}}{}^{3} + F_{\text{ET2}} \cdot F_{\text{PBOut}}{}^{2} + F_{\text{ET1}} \cdot F_{\text{PBOut}} + F_{\text{ET0}}\right) \tag{6.3}$$

The power block load requirement must be within the limits defined by the minimum turbine input $Q_{\text{toPBMin}}$ and the maximum turbine input $Q_{\text{toPBMax}}$.

## TES maximum storage capacity

The TES maximum storage capacity $Q_{\text{inTESMax}}$ is a function of the equivalent full load hours of TES $N_{\text{HoursofStorage}}$ on the storage page and the design turbine thermal input $Q_{\text{PBDesign}}$ on the Power Block page:

$$Q_{\text{inTESMax}} = N_{\text{HoursOfStorage}} \cdot Q_{\text{PBDesign}} \tag{6.4}$$

## Storage dispatch levels

After a period of no operation, a system with TES will only start in an hour when the energy in the TES $Q_{\text{inTES}}$ is greater than the storage dispatch level for that hour. Two storage dispatch levels apply, depending on whether the solar field energy is greater than zero, $Q_{\text{WithSolar}}$, or zero, $Q_{\text{WithoutSolar}}$. The two dispatch levels are functions of the storage dispatch fraction values $F_{\text{WithSolar}}$ and $F_{\text{WithoutSolar}}$, the maximum energy storage $Q_{\text{inTESMax}}$ on the Storage page, and the TOU schedule on the Utility Rates page. Like the power block load requirement, each hour is assigned a different set of storage dispatch fractions based on the TOU schedule.

$$Q_{\text{WithSolar}} = F_{\text{WithSolar}} \cdot Q_{\text{inTESMax}} \tag{6.5}$$

$$Q_{\text{WithoutSolar}} = F_{\text{WithoutSolar}} \cdot Q_{\text{inTESMax}} \tag{6.6}$$

## TES charge and discharge rates

The maximum TES charge and discharge rates are the maximum power to storage and maximum power from storage values on the Storage page. Although these values are rates with units of MWh/h, they are used in equations with energy values in units of kWh because the rate values are all averaged over a one hour period, and therefore have units of MWh/h x 1 h.

The values of the maximum charge and discharge rates depend on whether or not the system has a heat exchanger.

### Systems with a heat exchanger

The system has a heat exchanger only when the solar field HTF on the Power Block page and storage fluid number on the Storage page are different. When a heat exchanger is present, the heat exchanger duty is a function of the solar multiple, and has a minimum value of one:

$$F_{\text{HeatExchangerDuty}} = F_{\text{SolarMultiple}} - 1 \tag{6.7}$$

The maximum charge and discharge rates are functions of the heat exchanger duty, the design turbine thermal input $Q_{\text{PBDesign}}$ on the Power Block page, and  the turbine TES adjustment - efficiency $F_{\text{TESAdjustEfficiency}}$ and turbine TES adjustment - gross output $F_{\text{TESAdjustOutput}}$ on the Storage page:

$$Q_{\mathrm{toTESMax}} = F_{\mathrm{HeatExchangerDuty}} \cdot Q_{\mathrm{PBDesign}} \tag{6.8}$$

$$Q_{\mathrm{fromTESMax}} = Q_{\mathrm{toTESMax}} \cdot \frac{F_{\mathrm{TESAdjustOutput}}}{F_{\mathrm{TESAdjustEfficiency}}} \tag{6.9}$$

**Systems without a heat exchanger**

When the solar field HTF on the Solar Field page and storage fluid number on the Storage page are the same, the system has no heat exchanger.

The maximum charge and discharge rates are functions of the design turbine thermal input $Q_{\mathrm{PBDesign}}$ and maximum over design operation fraction $F_{\mathrm{PBMax}}$ on the Power Block page, and the turbine TES adjustment - efficiency $F_{\mathrm{TESAdjustEfficiency}}$ and the turbine TES adjustment - gross output $F_{\mathrm{TESAdjustOutput}}$ on the Storage page:

$$Q_{\mathrm{toTESMax}} = Q_{\mathrm{PBDesign}} \cdot F_{\mathrm{PBMax}} \cdot F_{\mathrm{SolarMultiple}} \tag{6.10}$$

$$Q_{\mathrm{fromTESMax}} = Q_{\mathrm{PBDesign}} \cdot \frac{F_{\mathrm{TESAdjustOutput}}}{F_{\mathrm{TESAdjustEfficiency}}} \tag{6.11}$$

### Start-up energy requirement

The required start-up energy $Q_{\mathrm{StartUpRequired}}$ is the thermal energy required to bring the system to operating temperature after a period of non-operation. It is a function of the design turbine thermal input $Q_{\mathrm{PBDesign}}$ and the turbine start-up energy fraction $F_{\mathrm{StartUp}}$ on the Power Block page:

$$Q_{\mathrm{StartUpRequired}} = F_{\mathrm{StartUp}} \cdot Q_{\mathrm{PBDesign}} \tag{6.12}$$

## 6.3 Dispatch without TES

The system is considered to not have a thermal energy storage (TES) system when the equivalent full load hours of TES value on the Storage page is zero. For systems without storage, the dispatch strategy depends on the following:

- Power block operating mode in previous hour
- Energy available from the solar field in the current hour.

There are four dispatch modes for systems without storage. Each mode (A, B, C, and D) is described qualitatively below and then shown in more detail in the figures that follow.

Start-up energy is required to heat the system components when the power block did not operate in the previous hour. (The start-up energy requirement $Q_{\mathrm{StartUpRequired}}$ calculation is described in the Dispatch Parameters section.) The actual start up energy $Q_{\mathrm{StartUp}}$ is reported in the hourly results.

When start-up energy is required:

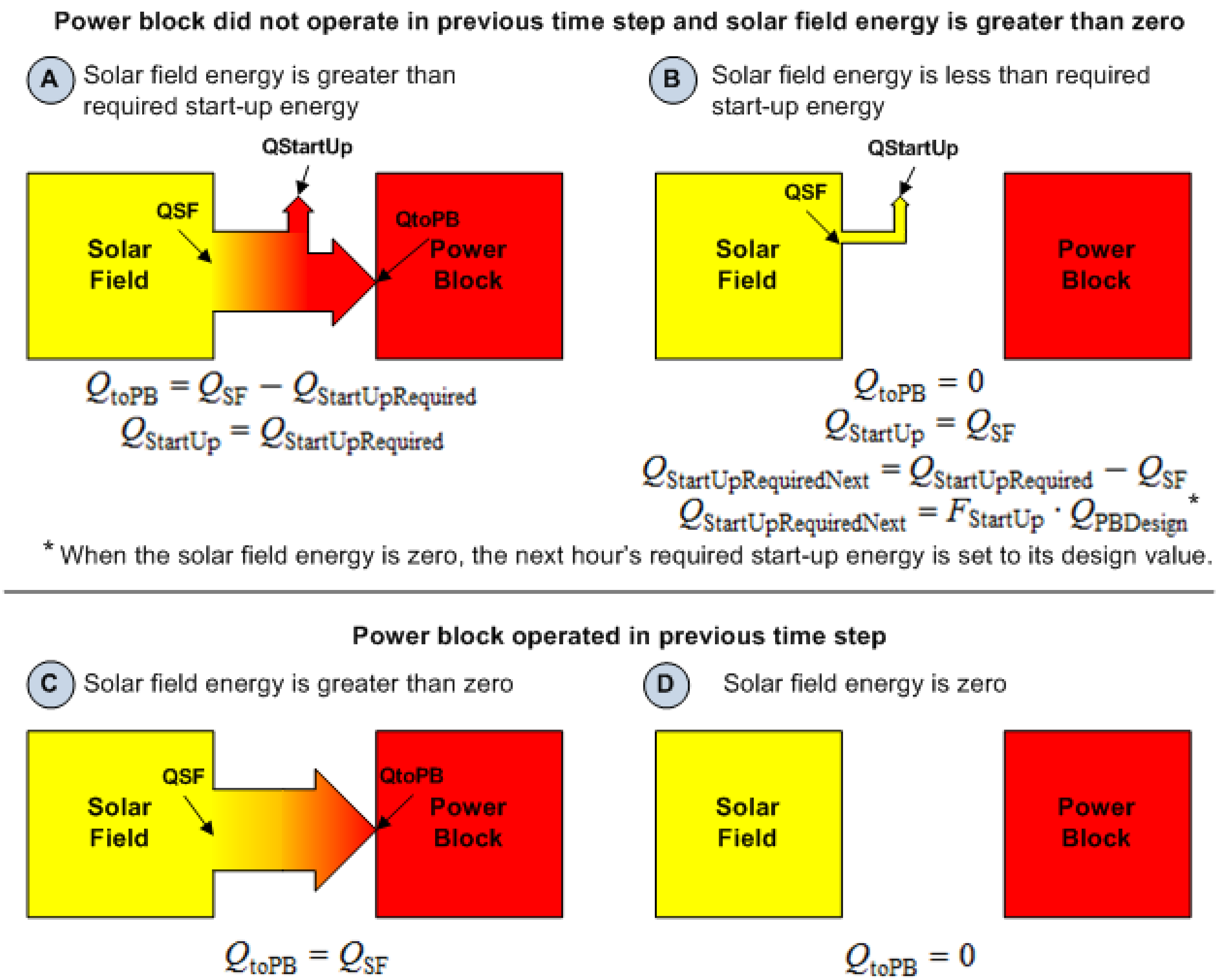
- When energy from the solar field exceeds the required start-up energy requirement, any surplus energy not required for warm-up goes to the power block to drive the turbine. For these hours, the power block starts and both a start-up energy and energy delivered to the power block value are reported in the hourly results. A

- For hours when energy from the solar field is not sufficient to start the turbine, the start-up energy is set to the solar field energy, and the power block does not start. The required start-up energy for the next hour is adjusted to account for the energy used to warm up the system in the current hour. B

When the power block did operate in the previous hour, no start-up energy is required:

- When the solar field energy is greater than zero, the solar field drives the power block. C
- When there is no solar field energy, the power block does not operate. D

**Fig 6.1. Dispatch without TES**




## 6.4 Dispatch with TES

Systems with a non-zero equivalent full load hours of TES on the Storage page are considered to have a storage system. For systems with storage, the energy dispatch depends on the following:

- Power block operating mode in previous hour
- Quantity of energy in storage in current hour
- Energy available from the solar field in current hour
- Time of day and storage dispatch fraction value assigned to the time of day

The following limits are set by the minimum and maximum values defined on the Power Block and Storage pages. These limits are described in the Dispatch parameters section above:

- Energy in TES never exceeds the maximum energy storage value on the Storage page
- Energy to and from the TES never exceeds the maximum and minimum values on the Storage page.
- Energy to the power block is limited by the power block input limits defined by the maximum over design operation and minimum load defined on the Power Block page.

There are nine dispatch modes for systems with storage. Four modes (A, B, C, and D) apply during start-up, and five (E, F, G, H, and I) apply during operation. Each dispatch mode is described qualitatively below, and then shown in more detail in the figures that follow.

### 6.4.1 Start-up

Start-up energy is required to heat the system components when the power block did not operate in the previous hour, and must be supplied by either the solar field or the TES. (The start-up energy requirement $Q_{\mathrm{StartUpRequired}}$ calculation is described in the Dispatch Parameters section.) The actual start-up energy $Q_{\mathrm{StartUp}}$ is reported in hourly results. For systems with storage, the actual start-up energy is equal to the required start-up energy. SAM dispatches energy to the TES before using it for start-up, so start-up energy is always subtracted from the energy from TES $Q_{\mathrm{fromTES}}$.

When the power block did not operate in the previous hour, there is sufficient energy to start it in the current hour when any of the following conditions are met:

- Solar field energy is greater than zero and the energy in TES is greater than the "without solar" dispatch level $Q_{\mathrm{WithoutSolar}}$.
- Solar field energy is zero and the energy in TES is greater than the "with solar" dispatch level $Q_{\mathrm{WithSolar}}$.
- Solar field energy is greater than the maximum TES charge rate $Q_{\mathrm{toTESMax}}$.

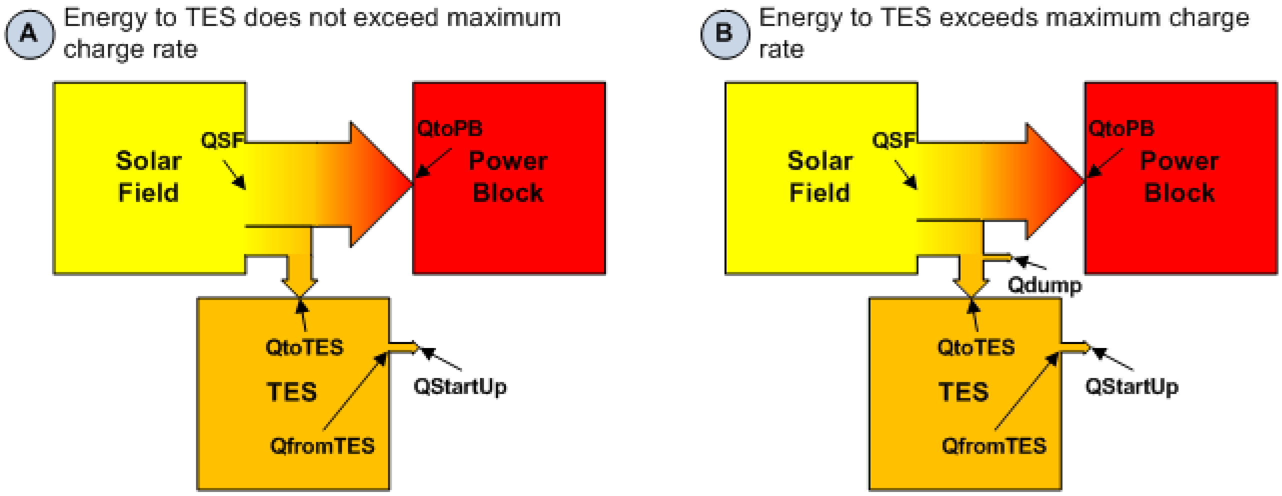
If the above conditions are not met, there is insufficient energy to start the system.

**Sufficient energy to start the system:**

- When the solar field energy $Q_{\mathrm{SF}}$ exceeds the amount required to run the power block $Q_{\mathrm{PBLoad}}$, TES is charged. A
- If the energy available to charge the TES exceeds the maximum charge rate $Q_{\mathrm{toTESMax}}$, thermal energy is dumped. B
- When the solar field energy cannot meet the power block load requirement, any energy in the TES is used to drive the power block. C

**Fig 6.2. Dispatch with TES during start-up**

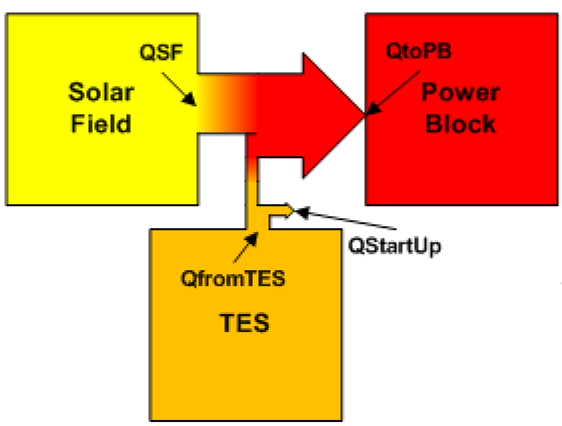
**Solar field energy is greater than load requirement**




$$Q_{\text{toPB}} = Q_{\text{PBLoad}}$$
$$Q_{\text{toTES}} = Q_{\text{SF}} - Q_{\text{toPB}}$$
$$Q_{\text{fromTES}} = Q_{\text{StartUp}}$$

$$Q_{\text{toPB}} = Q_{\text{PBLoad}}$$
$$Q_{\text{toTES}} = Q_{\text{toTESMax}}$$
$$Q_{\text{Dump}} = Q_{\text{toTES}} - Q_{\text{toTESMax}}$$
$$Q_{\text{fromTES}} = Q_{\text{StartUp}}$$

C **Solar field energy is less than or equal to load requirement**




$$Q_{\text{toTES}} = 0$$
$$Q_{\text{fromTES}} = Q_{\text{StartUp}} + \left(1 - \frac{Q_{\text{SF}}}{Q_{\text{toPB}}}\right) \cdot Q_{\text{fromTESMax}}^{*}$$
$$Q_{\text{toPB}} = Q_{\text{SF}} + \left(1 - \frac{Q_{\text{SF}}}{Q_{\text{toPB}}}\right) \cdot Q_{\text{fromTESMax}}$$

*When energy from TES is greater than maximum charge rate:

$$Q_{\text{fromTES}} = Q_{\text{fromTESMax}}$$

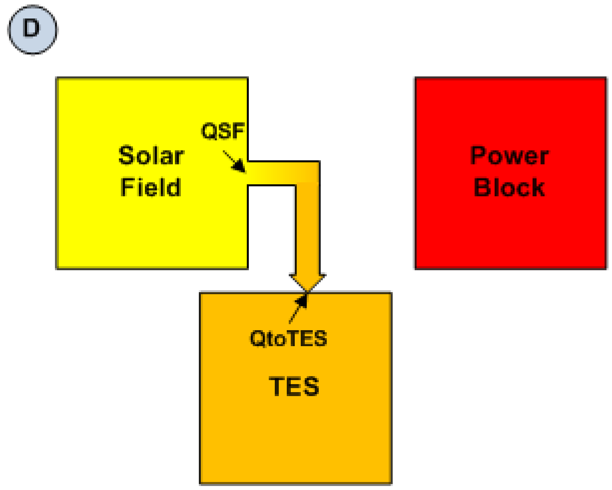
For hours when the power block starts, the energy remaining in the TES $Q_{\text{inTESnext}}$ at the beginning of the next hour is a function of the energy in the TES in the current hour $Q_{\text{inTES}}$, the start up energy $Q_{\text{StartUp}}$, the solar field energy $Q_{\text{SF}}$, and the energy to the TES $Q_{\text{toTES}}$:

$$Q_{\text{inTESNext}} = Q_{\text{inTES}} - Q_{\text{StartUp}} + (Q_{\text{SF}} - Q_{\text{toPB}}) \quad (6.13)$$

**Insufficient energy to start the system:**

- All solar field energy $Q_{\text{SF}}$ charges the TES. D

**Fig 6.3. Dispatch with TES and insufficient start-up energy**




$$Q_{\text{toPB}} = 0$$
$$Q_{\text{fromTES}} = 0$$
$$Q_{\text{toTES}} = Q_{\text{SF}}$$

Four hours when there is insufficient energy to start the power block, the energy remaining in the TES $Q_{\text{inTESnext}}$ at the beginning of the next hour is a function of the energy in the TES in the current hour $Q_{\text{inTES}}$, and the energy to the TES $Q_{\text{toTES}}$:

$$Q_{\text{inTESNext}} = Q_{\text{inTES}} + Q_{\text{toTES}} \tag{6.14}$$

## 6.4.2 Power block operating

When the power block operated in the previous hour, energy is supplied to the power block by either the solar field, TES, or both.

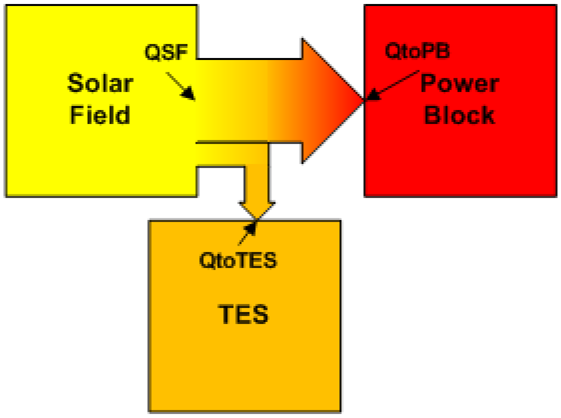
**Sufficient energy to drive power block**

When the sum of the energy from the solar field $Q_{\text{SF}}$ and energy in storage $Q_{\text{inTES}}$ is greater than the power block load requirement $Q_{\text{PBLoad}}$, there is sufficient energy to drive the power block at its design point:

- When the solar field energy $Q_{\text{SF}}$ exceeds the power block load requirement $Q_{\text{PBLoad}}$, the solar field drives the power block and charges the TES. E
- If the power block load requirement is met and the TES is being charged at the TES maximum charge rate $Q_{\text{toTESMax}}$, then excess thermal energy is dumped. F
- When the solar field energy is less than or equal to the power block requirement, the energy from the TES supplements the solar field energy to drive the power block until the remaining energy in the TES falls below the power block minimum load $Q_{\text{toPBMin}}$. This condition would typically occur during summer nights. G

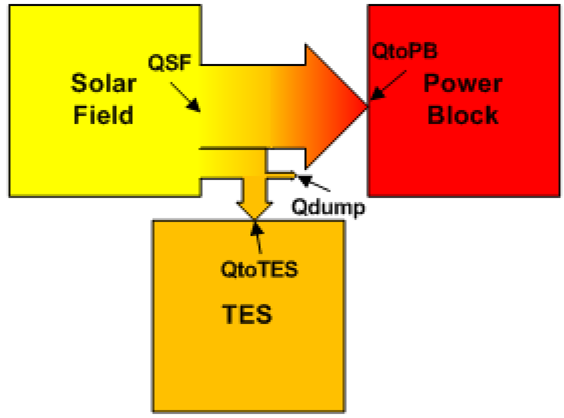
**Fig 6.4. Dispatch with TES and sufficient energy to drive power block at design point**

E Solar field energy exceeds power block load requirement



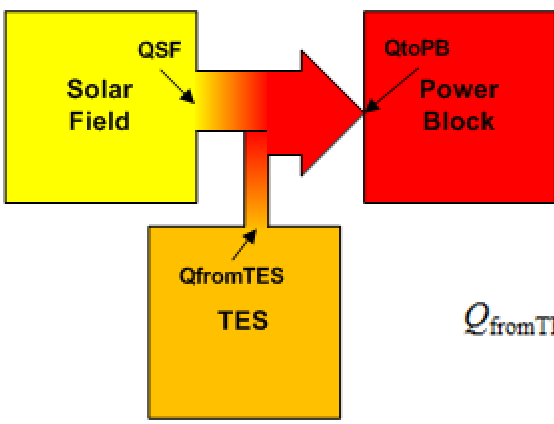

$$Q_{\text{toTES}} = Q_{\text{SF}} - Q_{\text{toPB}}$$
$$Q_{\text{fromTES}} = 0$$
$$Q_{\text{toPB}} = Q_{\text{PBLoad}}$$

F Solar field energy exceeds total maximum power block input and TES maximum charge rate




$$Q_{\text{toTES}} = Q_{\text{toTESMax}}$$
$$Q_{\text{fromTES}} = 0$$
$$Q_{\text{toPB}} = Q_{\text{PBLoad}}$$
$$Q_{\text{Dump}} = Q_{\text{toTES}} - Q_{\text{toTESMax}}$$

G Solar field energy is less or equal to power block load requirement




$$Q_{\text{toTES}} = 0$$
$$Q_{\text{fromTES}} = Q_{\text{StartUp}} + \left(1 - \frac{Q_{\text{SF}}}{Q_{\text{PBLoad}}}\right) \cdot Q_{\text{fromTESMax}}$$
$$Q_{\text{toPB}} = Q_{\text{fromTES}} + Q_{\text{SF}}$$

The energy remaining in the TES $Q_{\text{inTESnext}}$ at the beginning of the next hour is a function of the energy in the TES in the current hour $Q_{\text{inTES}}$, the solar field energy $Q_{\text{SF}}$, the energy to the TES $Q_{\text{toTES}}$, and any dumped thermal energy $Q_{\text{Dump}}$:

$$Q_{\text{inTESNext}} = Q_{\text{inTES}} + Q_{\text{SF}} - Q_{\text{toPB}} - Q_{\text{Dump}} \tag{6.15}$$

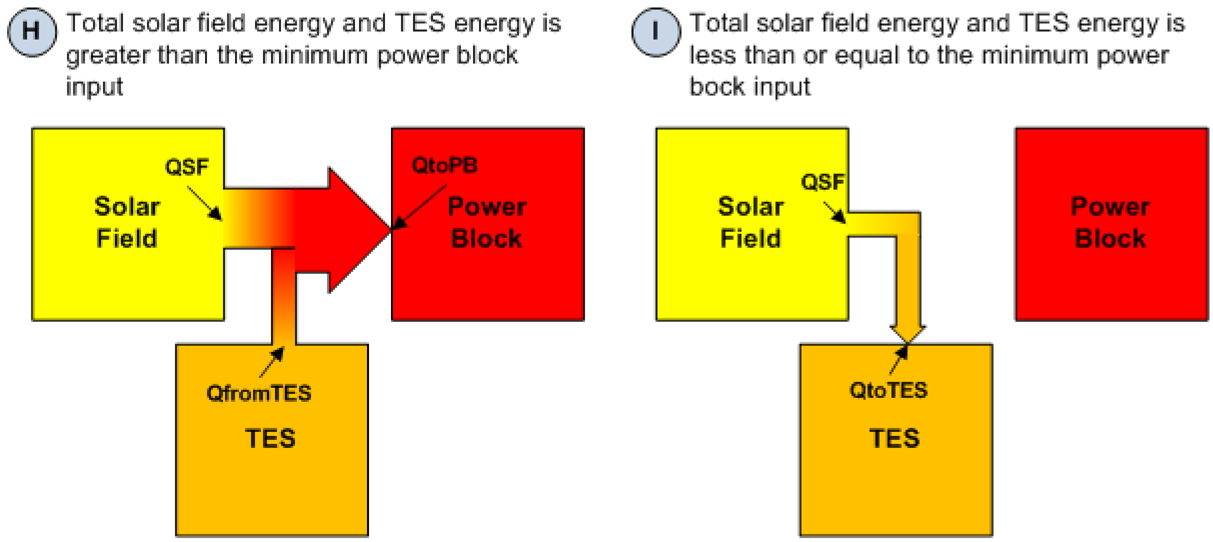
**Solar field energy is insufficient to drive power block**

When the sum of the energy from the solar field $Q_{\text{SF}}$ and energy in storage $Q_{\text{inTES}}$ is less than or equal to the power block load requirement $Q_{\text{PBLoad}}$, there is insufficient energy to drive the power block at its design point. The power block either runs at part load or does not run:

- When the sum of the solar field energy and energy in the TES is greater than the minimum power block input $Q_{\text{toPBMin}}$, the solar field and TES both drive the power block at part load, and the TES H empties.

- When the sum of the solar field energy and energy in the TES is less than or equal to the minimum power block input, all of the solar field energy is used to charge the TES. I

**Fig 6.5. Dispatch with TES and insufficient energy to drive power block at design point**




$$Q_{\text{toPB}} = Q_{\text{SF}} + Q_{\text{inTES}}$$
$$Q_{\text{fromTES}} = Q_{\text{inTES}}$$
$$Q_{\text{toPB}} = 0$$
$$Q_{\text{inTESNext}} = 0$$

$$Q_{\text{toPB}} = 0$$
$$Q_{\text{fromTES}} = 0$$
$$Q_{\text{toTES}} = Q_{\text{SF}}$$
$$Q_{\text{inTESNext}} = Q_{\text{inTES}} + Q_{\text{toTES}}$$

## 6.5 TES losses and freeze protection

After calculating the energy in storage at the beginning of the next hour $Q_{\text{inTESNext}}$, SAM adjusts the quantity to account for thermal heat loss from the storage tank and any freeze protection energy supplied by the TES. For systems without TES, freeze protection energy is supplied by an auxiliary heater.

### TES HTF pump load factor

The TES HTF pump load factor is used to calculate the parasitic electric losses from the TES hot HTF pumps described in the Parasitics chapter. For hours when the power block operates, the TES pump load factor $F_{\text{TESPumpLoad}}$ is a function of the thermal energy from the TES $Q_{\text{fromTES}}$ and the design turbine thermal input on the Power Block page:

$$F_{\text{TESPumpLoad}} = \frac{Q_{\text{FromTES}}}{Q_{\text{PBDesign}}} \qquad (7.1)$$

For hours when the power block does not operate, the TES pump load factor is set to zero.

### Losses

The adjusted energy in storage at the beginning of the next hour is a function of the tank heat loss $Q_{\text{TankHeatLoss}}$ from the Storage page and the freeze protection energy supplied by the TES $Q_{\text{FreezeProtectTES}}$:

$$Q_{\mathrm{inTESNextAdj}} = Q_{\mathrm{inTESNext}} - (Q_{\mathrm{TankHeatLoss}} + Q_{\mathrm{FreezeProtectTES}}) \tag{6.16}$$

### Freeze protection

Freeze protection energy prevents the heat transfer fluid temperature from dropping below its freezing point. The solar field module calculates the required freeze protection energy $Q_{\mathrm{HTFFreezeProtect}}$, which must either be supplied by the TES $Q_{\mathrm{FreezeProtectTES}}$ or by an an auxiliary fossil fuel-fired heater $Q_{\mathrm{FreezeProtectHtr}}$.

For systems without TES, all freeze protection energy is supplied by the auxiliary heater:

$$Q_{\mathrm{FreezeProtectHtr}} = Q_{\mathrm{HTFFreezeProtect}} \tag{6.17}$$

For systems with TES, all freeze protection energy is supplied by the TES:

$$Q_{\mathrm{FreezeProtectTES}} = Q_{\mathrm{HTFFreezeProtect}} \tag{6.18}$$

# 7 Parasitics

The parameters on the Parasitics page are used by the solar field, storage, and power block simulation modules to calculate losses due to parasitic electric loads throughout the system. The total parasitic losses $E_{\mathrm{Parasitics}}$ is the sum of the parasitic losses calculated by each simulation module.

## 7.1 User Input Variables

The input variables on the Parasitics page are used in the three modules of SAM's simulation module: Solar field, power block and storage. The input variables are described qualitatively in the tables below. More detailed descriptions with equations are in the section that follows.

Each parasitic loss type has a set of parameters that includes a Factor and design point value, and in some cases a PF and F0, F1, and F2 factor. These parameters are indicated by the following symbols in the equations described later in this chapter:

**Table 7.1. Parasitic loss parameter symbols**

| Name | Symbol |
|---|---|
| Factor | $F_{\mathrm{Par}<\boldsymbol{Name}>}$ |
| PF | $F_{\mathrm{ParPF}<\boldsymbol{Name}>}$ |
| F0 | $F_{\mathrm{Par}<\boldsymbol{Name}>0}$ |
| F1 | $F_{\mathrm{Par}<\boldsymbol{Name}>1}$ |
| F2 | $F_{\mathrm{Par}<\boldsymbol{Name}>2}$ |
| Design Point Parasitics | $F_{\mathrm{Par}<\boldsymbol{Name}>\mathrm{D}}$ |

**Table 7.2. Parasitics input variables used by all modules**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Solar Field | The solar field type. SAM stores a set of parasitic parameters for six solar field types. Custom parameter sets can also be defined by clicking the Library button. | -- | -- |
| Solar Field Area | The design point calculated solar field area from the Solar Field page | m2 | ASolarField |
| Total Design Parasitics | The sum of collector drives and electronics, solar field HTF pump, night circulation pumping, power block fixed, balance of plant, heater/boiler, and cooling towers design loss values. Provided for reference only, not used in simulation calculations. | MWe | -- |

**Table 7.3. Parasitics input variables Calculated in the Solar Field module**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Collector Drives and Electronics | Electrical losses from electric or hydraulic SCA drives that position the collector to track the sun and from electronic SCA tracking controllers and alarm monitoring devices. Calculated as a function of the solar field area. | MWe | EParSFD |
| Solar Field HTF Pump | Electrical losses from cold HTF pumping in the solar field. Calculated as a function of the solar field area. These losses are calculated only in hours when the solar field is operating. | | EParHTFD |
| Antifreeze Pumping | Electrical losses from HTF pumps in the solar field. Calculated as a function of the solar field area. These losses are used only in hours when the solar field is not operating. | MWe | EParAntiD |

**Table 7.4. Parasitics input variables calculated in the Storage module**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Thermal Energy Storage Pumps | Electrical losses from pumps in the TES system. Calculated as a function of the gross turbine output. Note that the F0, F1, and F2 factors are not used. | | EPARTESD |

**Table 7.5. Parasitics input variables calculated in the Power Block module**

| Name | Description | Units | Symbol |
|---|---|---|---|
| Power Block Fixed | These fixed losses apply 24 hours per day. | MWe | EParPBFixedD |
| Balance of Plant | Electrical losses that apply in hours when the power block operates at part or full load. Calculated as a function of power block load. | MWe | EParBOP |
| Heater/Boiler | Losses that apply only when the fossil back-up heater is in operation.Calculated as a function of the heater load. | MWe | EParHtr |
| Cooling Towers | The cooling tower parasitic losses are electrical losses that occur when the power block operates at part or full load. Calculated either as a function of power block load or at a fixed 50% or 100% of the design cooling tower parasitic losses. | MWe | EParCTD |
| Cooling Tower Operation Mode | Determines how cooling tower parasitic losses are calculated. For "Cooling Tower at 50% or 100%," parasitic losses are calculated as 50% of the design cooling tower parasitic losses when the power block load is 0.5 or less, and as or 100% of the design parasitic losses when the power block load is greater than 0.5. For "Cooling Tower parasitics a function of load," cooling tower parasitic losses are calculated as a function of power block load. | -- | -- |

## 7.2 Parasitic Losses

The solar field, power block and storage simulation modules each calculate components of the total parasitic losses using parameters from the Parasitics page. The total parasitics EParasitics is the sum of these values:

$$E_{\text{Parasitics}} = E_{\text{ParSF}} + E_{\text{ParTES}} + E_{\text{ParPB}} \tag{7.2}$$

### 7.2.1 Solar Field

The solar field module calculates three parasitic losses:

- Collector drive and electronics losses are associated with the drive mechanisms on each SCA and with the power requirements of electronic SCA drive controllers and alarm circuitry.
- HTF pumping losses are associated with the solar field's cold HTF pumps during solar field operation.
- Antifreeze pumping losses are associated with the solar field HTF pumps during the night.

The total solar field parasitic losses EParSF is the sum of the three solar field parasitic losses:

$$E_{\text{ParSF}} = E_{\text{ParSCADrives}} + E_{\text{ParHTFPump}} + E_{\text{ParAntiFreeze}} \tag{7.3}$$

### Collector (SCA) drive and electronics losses

The SCA drive and electronic losses $E_{\text{ParSCADrives}}$ depend on the solar field load in the current hour. When the solar field load is greater than zero, these losses are equal to their design value shown on the Parasitics page:

$$E_{\text{ParSCADrives}} = E_{\text{ParSCADrivesD}} \tag{7.4}$$

The design SCA drive and electronics losses $E_{\text{ParSCADrivesD}}$ is a function of the design gross turbine output

$E_{Design}$, and the loss factors $F_{ParSCADrives}$ and $F_{ParPFSCADrives}$ in the Factor and PF columns on the Parasitics page, respectively:

$$E_{ParSCADrivesD} = F_{ParSCADrives} \cdot F_{ParPFSCADrives} \cdot E_{Design} \tag{7.5}$$

For hours when the solar field load is zero, the SCA drive and electronic losses are set to zero:

$$E_{ParSCADrives} = 0 \tag{7.6}$$

### HTF pumping losses

The HTF pumping losses $E_{ParHTFPump}$ also depend on the solar field load in the current hour. When the solar field load is greater than zero, the pumping losses are a function of the solar field load $F_{SFLoad}$ calculated by the Solar Field module, design HTF pumping losses $E_{ParHTFPumpD}$, and the three HTF pumping loss coefficients $F_{ParHTFPump0}$, $F_{ParHTFPump1}$, and $F_{ParHTFPump2}$:

$$E_{ParHTFPump} = E_{ParHTFPumpD} \cdot \left(F_{ParHTFPump2} \cdot F_{SFLoad}^{\ 2} + F_{ParHTFPump1} \cdot F_{SFLoad} + F_{ParHTFPump0}\right) \tag{7.7}$$

The design HTF pumping losses $E_{ParHTFPumpD}$ are a function of the HTF pump loss factors $F_{ParHTFPump}$ and $F_{ParPFHTFPump}$ in the Factor and PF columns of the Parasitics page:

$$E_{ParHTFPumpD} = F_{ParHTFPump} \cdot F_{ParPFHTFPump} \cdot A_{SolarField} \tag{7.8}$$

For hours when the solar field load is zero, the HTF pumping losses are set to zero:

$$E_{ParHTFPump} = 0 \tag{7.9}$$

### Antifreeze pumping losses

The antifreeze pumping losses occur when the solar field load is zero. When the solar field load is greater than zero, the antifreeze pumping losses are zero:

$$E_{ParAntiFreeze} = 0 \tag{7.10}$$

For hours when the solar field load is zero, the antifreeze pumping losses $E_{ParAntifreeze}$ are equal to the design antifreeze pumping losses:

$$E_{ParAntifreeze} = E_{ParAntifreezeD} \tag{7.11}$$

The design antifreeze pumping losses $E_{ParAntifreezeD}$ are a function of the design gross turbine output $E_{Design}$ and the antifreeze pumping loss factor $F_{ParAntifreeze}$:

$$E_{ParAntifreezeD} = F_{ParAntifreeze} \cdot E_{Design} \tag{7.12}$$

## 7.2.2 Storage

The dispatch and storage module calculates one parasitic loss:

- Electric parasitic losses from the thermal energy storage (TES) hot HTF pumps

The TES parastic losses $E_{ParTES}$ are a function of the TES HTF pump load factor $F_{TESPumpLoad}$, the design TES parasitic losses $E_{\text{ParTESD}}$, and parameters on the Parasitics page $F_{\text{ParTES0}}$, $F_{\text{ParTES1}}$, $F_{\text{ParTES2}}$:

$$E_{\text{ParTES}} = E_{\text{ParTESD}} \cdot \left(F_{\text{ParTES2}} \cdot F_{\text{TESPumpLoad}}{}^{2} + F_{\text{ParTES1}} \cdot F_{\text{TESPumpLoad}} + F_{\text{ParTES0}}\right) \tag{7.13}$$

The TES pump load factor $F_{\text{TESPumpLoad}}$ is calculated by the dispatch and storage module for each hour that the power block operates as a function of the thermal energy from the TES $Q_{\text{fromTES}}$ and the design trubine thermal input on the Power Block page:

$$F_{\text{TESPumpLoad}} = \frac{Q_{\text{FromTES}}}{Q_{\text{PBDesign}}} \tag{7.14}$$

The design TES parasitic losses shown on the Parasitics page are calculated based on the design gross turbine output $E_{\text{Design}}$ and the Factor and PF parameters $F_{\text{ParTES}}$ and $F_{\text{ParPFTES}}$:

$$E_{\text{ParTESD}} = F_{\text{ParTES}} \cdot F_{\text{ParPFTES}} \cdot E_{\text{Design}} \tag{7.15}$$

### 7.2.3 Power Block

The Power Block module calculates the following parasitic losses:

- Fixed power block
- Balance of plant
- Cooling towers
- Heater/boiler

The total power block parasitic losses is the sum of the four losses:

$$E_{\text{ParPB}} = E_{\text{ParPBFixed}} + E_{\text{ParBOP}} + E_{\text{ParCT}} + E_{\text{ParHtr}} \tag{7.16}$$

#### Fixed power block losses

The fixed power block losses are equal to the design fixed power block losses on the Parasitics page:

$$E_{\text{ParPBFixed}} = E_{\text{ParPBFixedD}} \tag{7.17}$$

The design fixed power block losses are a function of the power block fixed factor $F_{\text{ParPBFixed}}$ on the parasitics page and the design gross turbine output $E_{\text{Design}}$:

$$E_{\text{ParPBFixedD}} = F_{\text{ParPBFixed}} \cdot E_{\text{Design}} \tag{7.18}$$

#### Balance-of-plant losses

The balance-of-plant losses depend on the design gross turbine output, the power block load factor, and balance of plant parameters on the Parasitics page.

For hours when the power block load is greater than zero, the balance-of-plant losses are a function of the power block load factor $F_{\text{PBLoad}}$, the design balance-of-plant losses $E_{\text{ParBOPD}}$, and loss factors $F_{\text{ParBOP0}}$, $F_{\text{ParBOP1}}$, $F_{\text{ParBOP2}}$:

$$E_{\text{ParBOP}} = E_{\text{ParBOPD}} \cdot \left(F_{\text{PBLoad}} \cdot F_{\text{ParBOP2}}{}^{2} + F_{\text{PBLoad}} \cdot F_{\text{ParBOP1}} + F_{\text{ParBOP0}}\right) \tag{7.19}$$

The design balance-of-plant losses $E_{\text{ParBOPD}}$ are a function of the design gross turbine output $E_{\text{Design}}$ and the

Factor and PF parameters $F_{\text{ParBOP}}$ and $F_{\text{ParPFBOP}}$:

$$E_{\text{ParBOPD}} = F_{\text{ParBOP}} \cdot F_{\text{ParPFBOP}} \cdot E_{\text{Design}} \tag{7.20}$$

For hours when the power block load factor is zero, the balance-of-plant losses are zero:

$$E_{\text{ParBOP}} = 0 \tag{7.21}$$

## Cooling tower losses

The cooling tower losses depend on the power block load factor, cooling tower operating mode, and the cooling towers loss parameters on the Parasitics page.

For the cooling tower operating mode "Cooling Tower parasitics a function of load," during hours when the power block load factor is greater than zero , the cooling tower losses are a function of the power block load factor $F_{\text{PBLoad}}$, the design cooling tower losses $E_{\text{ParCTD}}$, and the loss factors $F_{\text{ParCT0}}$, $F_{\text{ParCT1}}$, $F_{\text{ParCT2}}$:

$$E_{\text{ParCT}} = E_{\text{ParCTD}} \cdot \left(F_{\text{PBLoad}} \cdot F_{\text{ParCT2}}{}^{2} + F_{\text{PBLoad}} \cdot F_{\text{ParCT1}} + F_{\text{ParCT0}}\right) \tag{7.22}$$

The design cooling tower losses $E_{\text{ParCTD}}$ are a function of the design gross turbine output $E_{\text{Design}}$ and the Factor and PF parameters $F_{\text{ParCT}}$ and $F_{\text{ParPFCT}}$:

$$E_{\text{ParCTD}} = F_{\text{ParCT}} \cdot F_{\text{ParPFCT}} \cdot E_{\text{Design}} \tag{7.23}$$

For the cooling tower operating mode "Cooling Tower at 50% or 100%", during hours when the power block load is greater than zero, the cooling tower losses are a function of the design cooling tower parasitics $E_{\text{ParCTD}}$. When the power block load factor is less than or equal to 0.5, the cooling tower parasitcs are set to fifty percent of the design losses:

$$E_{\text{ParCT}} = 0.5 \cdot E_{\text{ParCTD}} \tag{7.24}$$

When the power block load factor is greater than 0.5, the cooling tower parasitcs are equal to the design losses:

$$E_{\text{ParCT}} = E_{\text{ParCTD}} \tag{7.25}$$

For hours when the power block load factor is zero, the cooling tower parasitics are zero:

$$E_{\text{ParCT}} = 0 \tag{7.26}$$

## Heater (boiler) losses

The heater (boiler) losses depend on the heater load factor and the heater loss parameters on the Parasitics page.

For hours when the heater load factor is greater than zero, the heater losses are a function of the heater load factor $F_{\text{HtrLoad}}$, the design heater losses $E_{\text{ParHtrD}}$, and heater loss factors $F_{\text{ParHtr0}}$, $F_{\text{ParHtr1}}$, $F_{\text{ParHtr2}}$:

$$E_{\text{ParHtr}} = E_{\text{ParHtrD}} \cdot \left(F_{\text{HtrLoad}} \cdot F_{\text{ParHtr2}}{}^{2} + F_{\text{HtrLoad}} \cdot F_{\text{ParHtr1}} + F_{\text{ParHtr0}}\right) \tag{7.27}$$

The design heater losses $E_{\text{ParHtrD}}$ are a function of the design gross turbine output $E_{\text{Design}}$ and the Factor and PF parameters $F_{\text{ParHtr}}$ and $F_{\text{ParPFHtr}}$:

$$E_{\text{ParHtrD}} = F_{\text{ParHtr}} \cdot F_{\text{ParPFHtr}} \cdot E_{\text{Design}} \tag{7.28}$$

When the heater load factor is zero, the heater is not operating, and the heater losses are zero

$$E_{\mathrm{ParHtr}} = 0 \tag{7.29}$$

# 8 Hourly Results

Each simulation module described above calculates a set of output variables that are reported in the hourly results files, which are in a text file stored in trnSAM\CSP\output in the SAM folder, which is c:\SAM by default.

The data in the hourly results file can be viewed directly by opening the file in a text editor, or in an Excel spreadsheet by clicking Spreadsheet at the bottom on SAM's navigation menu. They can also be viewed graphically in the data viewer DView by clicking Time Series Graph.

This chapter describes the hourly output variables. The calculations are described in the relevant chapter above.

**Table 8.1. Hourly output variables calculated by the Solar Field module**

| Name | Name in Hourly Results | Description | Units | Symbol |
|---|---|---|---|---|
| Direct normal radiation | Q_nip | Direct normal radiation value read from the weather file. | $W/m^2$ | $Q_{\mathrm{NIP}}$ |
| Incident normal radiation | QSF_nipCosTh | Radiation in the solar field collector plane in thermal Watts. This value is reported in hourly results for reference, but not used in calculations. | MWt | $Q_{\mathrm{SFNIPCosTh}}$ |
| Direct normal insolation | Q_dni | The direct normal radiation incident on the solar field in thermal Watts. This value is reported in hourly results for reference, but not used in calculations. | MWt | $Q_{\mathrm{DNI}}$ |
| Absorbed solar energy | Q_abs | Thermal energy absorbed by the collectors. | $W/m^2$ | $Q_{\mathrm{Abs}}$ |
| Solar field absorbed energy | QSF_abs | The energy absorbed by the solar field before thermal losses and including optical losses. This value is reported in hourly results for reference, but not used in calculations. | MWt | $Q_{\mathrm{SFAbs}}$ |
| Solar field delivered energy | Q_SF(MW) | Thermal energy delivered by the solar field | MWt | $Q_{\mathrm{SolarField}}$ |
| Solar field pipe heat loss | QSF_Pipe_HL | Energy lost by header piping in the solar field. | MWt | $Q_{\mathrm{SFPipeLoss}}$ |
| Solar field HCE heat loss | QSF_HCE_HL | Energy lost by HCEs (receivers) in the solar field. | MWt | $Q_{\mathrm{HCELoss}}$ |

**Table 8.2. Hourly output variables calculated by the Power Block module**

| Name | Name in Hourly Results | Description | Units | Symbol |
|---|---|---|---|---|
| Gross turbine output | E_gross | Hourly turbine electric output from both solar and fossil sources, but not accounting for parasitic losses or availability. | MWe | $E_{\mathrm{Gross}}$ |
| Net electric generation | E_net | Net hourly turbine electric output from both solar and fossil sources accounting for parasitic losses, but not for availability. | MWe | $E_{\mathrm{Net}}$ |
| Parasitic losses | E_parasit | Total electric energy losses due to parasitic electrical loads in the system (pumps, control electronics, etc.) | MWe | $E_{\mathrm{Parasitics}}$ |
| Minimum turbine output | E_min | The calculated gross solar output during hours when the solar energy is insufficient to drive the turbine. This value is reported in the hourly results, but does not contribute to the power generation. | MWe | $E_{\mathrm{Min}}$ |
| Excess electricity | E_dump | For hours when the gross solar output exceeds the maximum over design output, the difference between the two is reported as excess electricity. This value does not contribute to power generation. | MWe | $E_{\mathrm{Dump}}$ |
| Fossil back-up energy | Q_gas | The thermal energy equivalent of the electric energy generated by the fossil fuel-fired backup boiler. | MWt | $Q_{\mathrm{Gas}}$ |

**Table 8.3. Hourly output variables calculated by the Dispatch and Storage module**

| Name | Name in Hourly Results | Description | Units | Symbol |
|---|---|---|---|---|
| Energy to thermal storage | Q_to_ts | Thermal energy delivered to TES | MWt | $Q_{\mathrm{toTES}}$ |
| Energy from thermal storage | Q_from_ts | Thermal energy from the TES | MWt | $Q_{\mathrm{fromTES}}$ |
| Energy to the power block | Q_to_PB | Thermal energy delivered to the power block. May include energy from the solar field, or energy from both the solar field and thermal storage. | MWt | $Q_{\mathrm{toPB}}$ |
| Dumped TES energy | Q_ts_Full | Thermal energy dumped when the TES is full. This happens in hours when the calculated energy in TES exceeds the maximum TES capacity $Q_{\mathrm{inTESMax}}$, described in Dispatch Parameters. | MWt | $Q_{\mathrm{TESDump}}$ |

| Name | Name in Hourly Results | Description | Units | Symbol |
|---|---|---|---|---|
| Dumped energy | Q_dump | Thermal energy dumped when either the energy delivered to either the power block or TES exceeds the maximum allowed. | MWt | $Q_{\text{Dump}}$ |
| Start up energy | Q_tur_SU | Energy required to start power block. This happens in hours when energy is available from the solar field or thermal storage and the power block did not operate in the previous hour. | MWt | $Q_{\text{PBStartup}}$ |
| Freeze protection energy from TES | Q_htfFPTES | Energy supplied by the TES when the heat transfer fluid temperature falls below its freezing point (defined by the minimum HTF temperature on the Solar Field page). | MWt | $Q_{\text{TESFreezeProtect}}$ |
| Freeze protection energy from auxiliary heater | Q_hftFpHtr | Energy supplied by the auxiliary heater when the heat transfer fluid temperature falls below its freezing point (defined by the minimum HTF temperature on the Solar Field page). | MWt | $Q_{\text{HTRFreezeProtect}}$ |
| Thermal storage heat loss | QTS_HL | Heat loss from the storage tank, equal to the tank heat losses on the Storage page. | MWt | $Q_{\text{TankHeatLoss}}$ |

SAM reports dumped thermal energy that result from two different conditions: